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Shear Stress-Strain Data for Structural Adhesives

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EXECUTIVE SUMMARY

The main objective of this investigation was to generate characteristic shear responses for several adhesives used for aerospace structural bonding applications. The shear responses consisted of shear stress-strain curves obtained by standardized tests and characterizing subsequent failure modes at three different environmental conditions. Six of these adhesives were film and the remaining were paste adhesive. In addition, the effects of heat and humidity on the apparent shear strength, shear modulus, and failure modes of each adhesive were investigated by testing at elevated temperatures with humidity-conditioned specimens. The characteristic shear responses were generated using the ASTM D 5656 thick adherend test method. The primary purpose of this report was to make this data available for use in future design and modeling efforts.

1. INTRODUCTION.

1.1 OBJECTIVES.

The main objective of this investigation was to generate characteristic shear responses for several adhesives used for aerospace structural bonding applications. This task involved generating characteristic shear stress-strain data at three different environmental conditions: room temperature dry (RTD), elevated temperature dry (ETD), and elevated temperature wet (ETW). This study generated characteristic shear responses for 18 different adhesive systems that are currently being investigated for use in manufacturing applications, as well as several that have been used historically in aircraft primary structural bonding. Six of these adhesives were film and the remaining were paste. In addition, the effects of heat and humidity on the apparent shear strength, shear modulus, and failure modes of each adhesive were investigated.

1.2 BACKGROUND.

The motivation for this study was the increased use of adhesive bonding in construction of general aviation aircraft. Additional impetus was to study the effects of elevated temperature on adhesive behavior as lower cure temperature (than previous military applications) is being used in such constructions. The adhesive strength and modulus were determined according to ASTM D 5656 (Standard Test Method for Thick-Adherend Metal Lap-Shear Joints for Determination of the Stress-Strain Behavior of Adhesives in Shear by Tension Loading [1]). Testing was conducted in three different environmental conditions: RTD, ETD (~180°F), and ETW (~180°F). The substrate material, provided by Cessna Aircraft Company of Wichita, Kansas, was phosphorically anodized 2024-T3 aluminum. Using the ASTM D 5656 test method, the effects of environment on the aircraft or subcomponent-bonded joint may be determined quantitatively. Combining this type of information with a thermal model for the aircraft will aid future designers in selecting the correct joint application in combination with the environmental exposure to be expected. The adhesive shear deformation was measured using two modified KGR-type port and starboard extensometers.

Thick adherend, recommended in ASTM D 5656, reduces the peel stress of lap joint specimens; therefore, test results may not represent the actual adhesive joint behavior. However, this method can be used to generate characteristic shear stress-strain curves and evaluate adhesive properties rather than adhesive joint properties. It should be noted that, although this test method is in common use, the method is very complicated, requiring careful specimen preparation, load introduction, and sensitive measurement instruments. One of the main purposes of this report was to present this information to allow one to do analysis of bonded joints (including nonlinear effects) and establish relevant failure models for structural joints in the future. This report also provides useful information for ongoing certification issues related to the application of lower temperature cure adhesive systems.

2. ADHESIVES.

To select the adhesives used for this investigation, several general aviation companies and personnel from the Federal Aviation Administration were consulted. Adhesives were supplied by Cessna Aircraft Company of Wichita, Kansas, and Cirrus Design Corporation of Duluth,

Minnesota. Some general information about various adhesives obtained from material vendors and aircraft companies is listed below.

- Film Adhesives

AF 126 – First generation epoxy film adhesive used in the aerospace industry for more than 30 years, thermosetting and nonvolatile for structural bonding of metals, excellent strength with a high degree of tack in the uncured state.

EA 9628 – Modified epoxy film adhesive designed for structural bonds requiring toughness, as applied in composite, metal, and honeycomb bonding.

EA 9695 – Bonding film adhesive with excellent environmental resistance used in composites structural repair, cure and cocure with composite laminates, and metal and honeycomb bonding.

EA 9696 – Moisture-resistant modified epoxy film used in composites structural repair, cure and cocure with composite laminates, and metal and honeycomb bonding; some space applications designed to withstand extremes of temperature, such as assemblies in the International Space Station.

FM 300 – 350°F cure structural adhesive used in the aerospace industry for more than 30 years in metal-to-metal and composite bonding.

FM 73 – Fracture-tough modified epoxy adhesive used in bonded repairs, and metal-to-metal and composite bonding applications, typically cured at 250°F for 1 hour; used in the U.S. Air Force's successful Primary Adhesively Bonded Structures Technology (PABST) program in the 1970s and currently used in bonded composite repair of cracked metallic aerospace structures, operational temperatures up to 180°F.

- Paste Adhesives

EA 9309.3 NA – Two-component paste-toughened adhesive with excellent peel strength containing 5 mil/0.13 m glass beads for bond line thickness control.

EA 9346.5 – One-component paste adhesive with a moderate viscosity, high-peel and shear strengths, and outstanding hot/wet properties for structural repairs, low viscosity wet layups, composite bonding, etc.

EA 9359.3 – Two-component paste adhesive system with excellent peel strength for bonding a variety of substrate materials and for structural repairs.

EA 9360 – Structural adhesive exhibiting excellent peel strength used for structural repairs, composite bonding, and liquid shim; service temperature up to 300°F.

- EA 9392 – Toughened adhesive with excellent shear strength at high temperatures and durable over a wide temperature range used for structural repair, potting, composites bonding, liquid shim, etc; service temperature up to 350°F.
- EA 9394 – Thixotropic adhesive with structural properties up to 350°F and a low peel strength used for potting, structural repair, composite bonding, liquid shim, and metal-composite bonding, i.e., titanium end fittings to composite parts.
- EA 9396 – Low viscosity adhesive with structural properties up to 350°F used for structural repair, composite bonding, and low viscosity wet layups.
- 3M DP-460 EG – Two-component epoxy adhesive with a low outgassing for potting, magnet bonding, hard disk drive assembly, bearing cartridge assembly (nontypical for aerospace structural bonding).
- 3M DP-460 NS – Two-component non-sag epoxy adhesive with an outstanding shear and peel at RTD, and high level of durability; non-sag formulation is excellent for vertical applications or any application requiring minimal adhesive flow from the bond line.
- 3M DP-820 – Two-component toughened acrylic adhesive with excellent shear and peel strength at RTD, good impact resistance and durability; bonded well to many metals, ceramics, wood, and most plastics; non-sag with 20 minute work-life.

3. TEST MATRIX.

The test matrix includes specimens in three different environmental conditions: RTD, ETD ~180°F, and ETW ~ 180°F. Two different cure cycles were investigated for EA 9360, EA 9392, and EA 9359.3 paste adhesives. A second cure cycle, similar to the first, was performed for an additional 48 hours under ambient conditions. Two replicates were proposed for each environmental condition. Testing was conducted according to the guidelines in ASTM D 5656. The thick adherend test method was used to minimize the peel stress from asymmetric loading. Table 1 shows the test matrix for eighteen different adhesive systems, including the six film and twelve paste adhesives.

TABLE 1. TEST MATRIX FOR TASK 1

Adhesive Name	Cure Cycle	Number of Coupons per Test Condition		
		RTD	ETD	ETW
AF 126	1	2	2	2
FM 73	1	2	2	2
EA 9628	1	2	2	2
EA 9696	1	2	2	2
EA 9695	1	2	2	2
FM 300	1	2	2	2
EA 9346.5	1	2	2	2
EA 9309.3 NA	1	2	2	2
EA 9394	1	2	2	2
EA 9396	1	2	2	2
3M DP-460 NS	1	2	2	2
3M DP-460 EG	1	2	2	2
3M DP-820	1	2	2	2
EA 9360	1	2	2	2
	2	2	2	2
EA 9392	1	2	2	2
	2	2	2	2
EA 9359.3	1	2	2	2
	2	2	2	2
MGS L418	1	2	2	2
PTM&W ES 6292	1	2	2	2
TOTAL		42	42	42

RTD – Room Temperature Dry (76°F) Testing Condition

ETD – Elevated Temperature Dry (180°F) Testing Condition

ETW – Elevated Temperature Wet (180°F) Testing Condition

4. PANEL FABRICATION AND MACHINING.

4.1 ADHESIVE TEST PANEL FABRICATION.

Specimens were fabricated according to the guidelines in the ASTM D 5656 standard. Test panels were fabricated using two 10- x 10-inch subpanels with a thickness of 0.375 inch, phosphoric-anodized and bond-primed, following ASTM D 3933, by Cessna Aircraft Company of Wichita, Kansas. The side with minimal surface scratches, especially in the test area, was selected to contact with the adhesive. On that face, two parallel lines were drawn 0.5 inch away from the centerline and perpendicular to the grain direction (figure 1). On the other face, 12 reference points were marked, and the thickness at each point was measured using a digital micrometer.

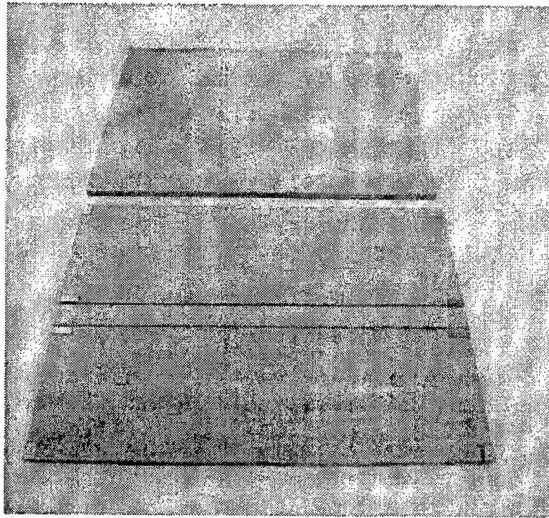


FIGURE 1. SPACER LOCATIONS FOR PASTE ADHESIVE TEST PANELS

Subpanels were grouped into sets of two, and reference points were marked so that bonded test panels would have the same reference point on both sides. Subpanel surfaces were cleaned several times with acetone and lint-free cotton towels, using a sweeping motion in the direction of the grain. This step in the process is important to ensure that the surface is adequately prepared for proper bonding of the aluminum-adhesive interface. Care was taken not to scratch the surface but to remove grease and other foreign substances. This procedure was repeated at least once to produce a clean surface. Poorly cleaned surfaces increase the chance of failure in an adhesive specimen, due to voids in the aluminum-adhesive interface.

Panels for six different film adhesives and twelve different paste adhesives were fabricated. To achieve a constant bond line thickness, brass shims/spacers were placed in specific areas using an aluminum template designed to position the spacers between specimens and the panel border. Care was taken not to leave any spacers in the gauge section. Once locations were marked using the template, spacers were bonded to the aluminum plate using either liquid glue (super glue) or double-sided tape. Following several iterations, the double-sided tape was found to provide a more even distribution of thickness than liquid glue. After the spacers were bonded, this subpanel surface was cleaned again with acetone.

Paste adhesives were applied in two different methods. Typically, the resin and accelerator were mixed in a cup using a prescribed mix-ratio and then applied to the subpanel. Another method used adhesives that were supplied in premeasured dual-syringe plastic Duo-Pak cartridges and then inserted into an applicator system. A nozzle attached to each applicator automatically mixed parts A and B. Each time a new cartridge was used, a small amount of adhesive was expelled before applying the remaining resin over the panel to avoid the use of any unmixed resin. Care was taken to evenly distribute the adhesive over the subpanel with the spacers and especially over the gauge section (figure 2). A thin layer of adhesive was applied over a second subpanel to provide a wet surface and diminish potential voids in the adhesive-aluminum interface. Immediately after that, the second subpanel was tilted and placed over the first subpanel to expel any trapped air.

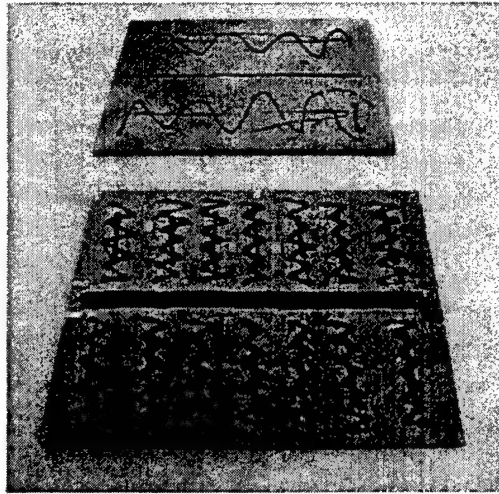


FIGURE 2. PASTE ADHESIVE APPLICATION FOR ASTM D 5656 TEST PANELS

For film adhesives, the required number of layers were cut and placed on one subpanel. After positioning each layer, the entire structure was rolled using a rubber roller to expel the trapped air between the surface and the film. To maintain a constant bond line thickness, a rectangular opening was cut in each layer to accommodate the spacers, using the same spacing template as in the paste adhesive panels.

Once the adhesive was applied, subpanels were taped with flash breaker tape to avoid any movement during the cure cycle. To ensure both plates were entirely closed, 4000 psi of pressure was applied using a 150-ton pneumatic press for 5 to 6 minutes. The plates were then vacuum bagged and maintained at an integrity of 27-in Hg (figure 3).

Each adhesive was cured according to the specified temperature and pressure obtained from the manufacturers data sheet (figure 4). A 3' x 5', 1000°F, 400-psi autoclave was used to regulate the cure process. The temperature control thermocouple monitored the adhesive temperature.

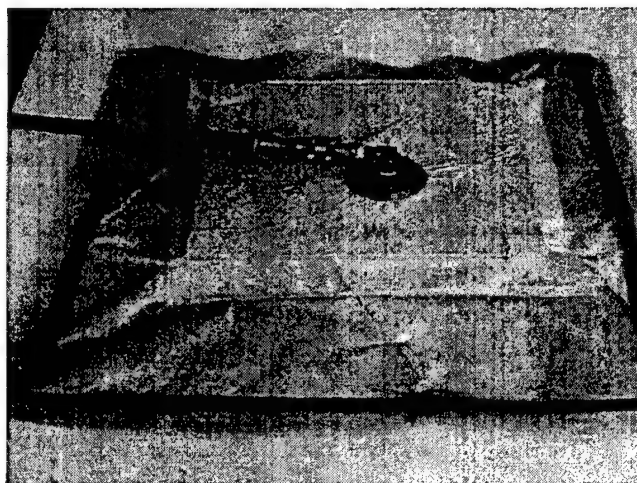


FIGURE 3. VACUUM BAGGING ADHESIVE TEST PANELS

Adhesive	Cure Temperature Range							Cure Method				
	73°F	120°F	160°F	180°F	200°F	245°F	260°F	345°F	360°F	Autoclave 50-55 psi	Oven Vacuum Bag >22 Hg	Room Temp.
Film Adhesives												
AF 126						60-90 minutes				✓		
EA 9628						60-90 minutes				✓		
EA 9695						60-90 minutes				✓		
EA 9696						60-90 minutes				✓		
FM300 (U065004)										✓		
FM73 (U064164)								60-90 minutes		✓		
Paste Adhesives												
EA 9309.3 NA						90-120 minutes					✓	
EA 9346.5							60-90 minutes			✓		
EA 9394 (U000941)						90-120 minutes				✓		
EA 9396 (U000940)						90-120 minutes				✓		
3M DP-460 NS	7 days											
3M DP-460 EG	24 hrs											
3M DP-820	48 hrs											
PTM&W ES 6292						1 hour						
MGS L418/418						3 hours						
EA 9360 (CC1)										✓		
EA 9360 (CC2)**						60 min				✓		
EA 9392 (CC1)						30 min				✓		
EA 9392 (CC2)**						60 min				✓		
EA 9359.3 (CC1)						30 min				✓		
EA 9359.3 (CC2)**						60 min				✓		
						30 min				✓		
♣ Post Cure: 5 hours at 180°-200°F												
▲ Post Cure: 10 hours at 175°-200°F												
*** Additional 48 hours at ambient temperature after cure cycle												
CC (Cure Cycle)												

FIGURE 4. CURE CYCLE INFORMATION ADHESIVE SYSTEMS USED IN TASK 1

Once the panels were cured, the final thickness was measured at the reference points in order to calculate the bond line thickness, which was used in two of the machining steps, discussed in the next section.

4.2 MACHINING OF ASTM D 5656 LAP SHEAR ADHESIVE SPECIMENS.

Adhesive lap shear specimens were machined according to the recommendations of ASTM D 5656 using a Bridgeport® CNC machine. Tool paths were created using MasterCam Version 7. First, the 1/2-inch loading pinholes were drilled and reamed with a 0.51-in reamer using the CNC machine, and panels were rough-cut into 1.25-in-wide strips using a band saw. These were cut oversized to avoid overheating and stressing of the adhesive, which can alter adhesive properties. Next, the specimen was machined (surface ground) to the final dimensions specified in ASTM D 5656. Eighth-in slots were made across the width of the specimen, resulting in a 0.375-in gauge section. Finally, 1/16-in pinholes were drilled on both sides of the gage section for the KGR-type extensometer attachment. CNC machining was conducted with abundant coolant to ensure that the specimens were not overheated during the machining process.

Following machining, for the purpose of tracking, specimens were named using the nomenclature shown in figure 5.

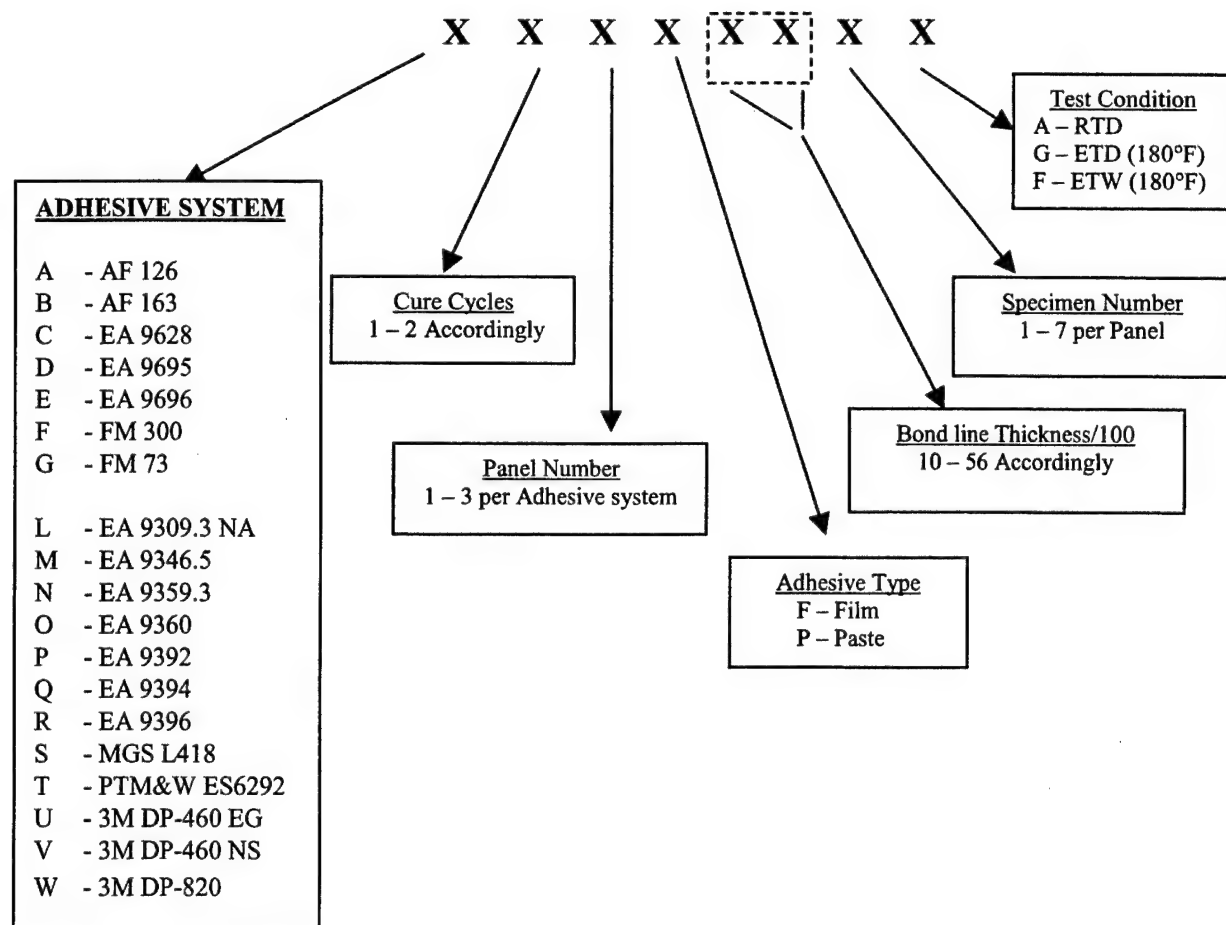


FIGURE 5. NOMENCLATURE FOR ADHESIVE TEST SPECIMENS

5. EXPERIMENTAL PROCEDURE.

5.1 SPECIMEN CONDITIONING AND DIMENSIONING.

Wet test specimens (ETW) were conditioned at 145°F and 85% relative humidity for 1000 hours (approximately 42 days) [2] in a humidity chamber in the NIAR Composites Laboratory at Wichita State University, Wichita, Kansas. Prior to this, ETW were dimensioned using digital calipers that automatically recorded the dimensions in a data file. Two gage-width readings and two gage-length readings were recorded. In addition, the adhesive thickness was calculated by subtracting the subpanel thickness obtained before specimen fabrication from the panel thickness after final fabrication.

5.2 TEST SETUP.

Adhesive lap shear testing was conducted according to the recommendations in the ASTM D 5656 standard (see figure 6). All testing was done in tension loading in the displacement control mode. Two self-aligning clevis fixtures were used at each end of the specimen to load it in tension. Half-inch steel bushings were inserted into the loading holes of the specimen, and 0.375" steel dowel pins were used to attach the specimen to the clevis arrangement. Experiments were performed on 22-kip MTS servohydraulic load frames at a rate of 0.05 in/min. Elevated temperature testing was conducted using a computer-controlled environmental chamber. The temperature of the chamber was monitored with a thermocouple taped to the gauge section of the specimen. Soak time for ETD and ETW specimens was 3 minutes after the gauge section reached the test temperature. The temperature was maintained within $\pm 3^\circ\text{F}$ of the targeted value of 180°F.

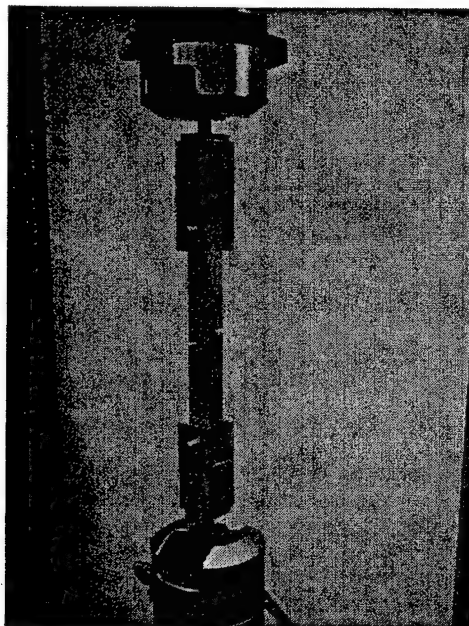


FIGURE 6. TEST SETUP FOR ASTM D 5656 ADHESIVE LAP SHEAR TEST

The displacement of the gauge section was recorded using two axial extensometers modified to function as KGR-type extensometers with four pin configurations. A detailed description of the KGR-type extensometer is discussed in the next section.

5.3 MODIFIED KGR-TYPE EXTENSOMETER.

The KGR extensometer [3] was modified to accommodate various bond line thicknesses. Two aluminum parts were attached to each arm of a MTS extensometer (figure 7). A fourth pin was added to the original KGR extensometer design to reduce the rotation and slippage of the extensometer attachment caused by peeling stresses [4 and 5]. The KGR-type extensometer used in this investigation was modified with knife edges so that extra calibration was not necessary. As the specimen extended in the loading direction, the knife edges allowed the extensometer arms to rotate so that the pins stayed perpendicular to the specimen.

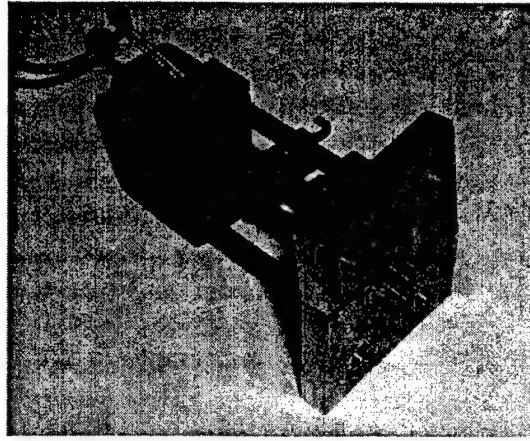


FIGURE 7. MODIFIED KGR-TYPE EXTENSOMETER (FOUR-PIN CONFIGURATION) FOR MEASURING ADHESIVE SHEAR STRAIN

5.4 DATA REDUCTION.

Data reduction was performed according to the ASTM D 5656 test standard. The apparent shear stress, τ_i , on the adhesive at each point was calculated using equation 1 below.

$$\tau_i = \frac{P_i}{A} \quad (1)$$

where P_i is the axial load and A is the initial overlap area (overlap length times width). The next step in the process was to find the adhesive shear strain. A correction for the displacement of the adherend that occurred between the pins and the adherend/adhesive interface, δ_m , was found by using equation 2,

$$\delta_m = \frac{p-t}{p} M \frac{L}{1000} F_a \quad (2)$$

where p is the average point gap and t is the bond line thickness. M is the metal displacement at 1000 lbf, as found in the all-aluminum dummy sample [1 and 4], and L is the load at displacement δ_a . F_a is the relationship between the all-aluminum correction factor and the simulated bond line thickness for $t_{simulated}$ given by equation 3a or 3b [6].

$$F_a = -1.73t_{simulated} + 1.065 \quad [t \sim \text{inches}] \quad (3a)$$

$$F_a = -0.0683 \cdot t_{simulated} + 1.065 \quad [t \sim \text{mm}] \quad (3b)$$

The shear strain, γ_i , at each point is calculated using equation 4, taken from the ASTM D 5656 standard, assuming a small-angle theory,

$$\gamma_i = \frac{\delta_a - \delta_m}{t} \quad (4)$$

where δ_a is the measured displacement of the KGR-type extensometer and δ_m is the ASTM correction factor for the adherend displacement that occurs between the measuring points and the adherend/adhesive interface.

The slope of the shear stress-strain curve in the initial linear range (figure 8) is the adhesive shear modulus, G . The adhesive shear modulus is found by

$$G = \frac{\Delta\tau}{\Delta\gamma} \quad (5)$$

where $\Delta\tau$ is the adhesive shear stress variation in the linear range and $\Delta\gamma$ is the adhesive shear strain variation in the linear range. To find the initial shear modulus from the adhesive shear stress-strain graph, a curve fit was applied to the initial linear section of the stress-strain curve. This is illustrated in figure 8, where the data points for the average reading of both KGR-type devices was curve fit. The slope of this line is defined as the adhesive shear modulus, G , in this report.

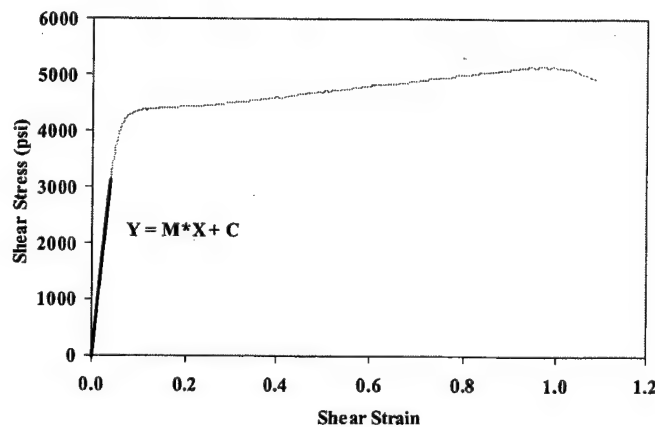


FIGURE 8. TYPICAL SHEAR STRESS-STRAIN CURVE FOR ADHESIVES

As seen from figure 8, one of the most distinguishing features of the test results using the ASTM D 5656 test method is the ability to characterize the adhesive shear response in the nonlinear range. These nonlinear results are extremely hard or impossible to obtain using other standard test methods and make the data presented in the report very valuable. This nonlinear data is needed for analytical models to predict failure of bonded joints.

5.5 FAILURE MODES OF ADHESIVE JOINTS.

To gain a full understanding of the properties of the adhesive and the joint being investigated, the mode of failure must be characterized. In adhesive technology, there are three typical characterizations for the failure mode of an adhesive joint (figure 9).

- Cohesive failure is characterized by failure of the adhesive itself.
- Adhesive failure is characterized by a failure of the joint at the adhesive/adherend interface and is typically caused by inadequate surface preparation, chemically and/or mechanically. Specimens that fail adhesively tend to have excessive peel stresses that lead to failure and often do not yield a strength value for the adhesive joint but rather indicate unsuitable surface qualities of the adherend.
- Substrate failure is characterized by failure of the adherend instead of the adhesive. In metals, this occurs when the adherend yields. In composites, the laminate typically fails by way of interlamina failure, i.e., when the matrix between plies fails. In substrates, failure occurs when the adhesive is stronger than the adherend in the joint being tested.

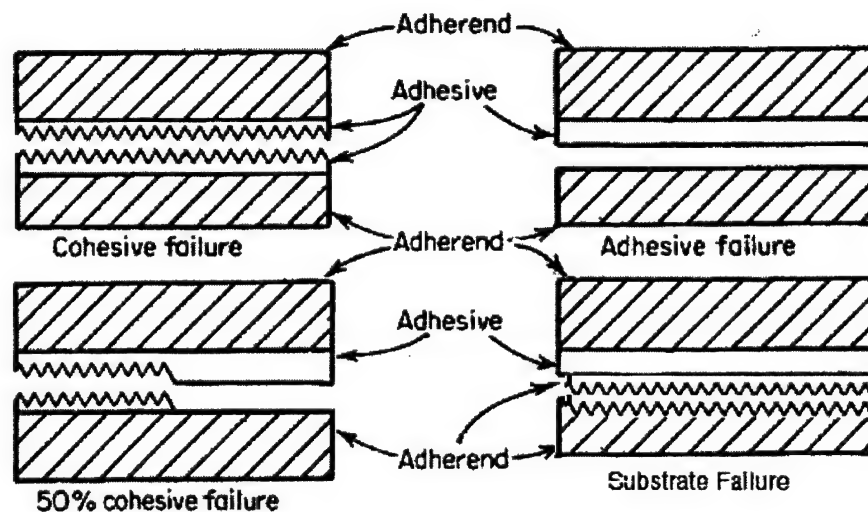


FIGURE 9. FAILURE MODES OF ADHESIVE TEST SPECIMENS

6. RESULTS AND DISCUSSION.

The apparent shear strength and shear modulus results for film and paste adhesives are summarized in tables 2 and 3, respectively. These results reflect the average value obtained from

two or three replicates. Figures 10 through 13 illustrate the apparent shear strength and shear modulus results for various adhesives. The details of the results presented in figures 10-13 are presented in appendix A, which show the characteristic stress-strain curves of each individual test. The results presented in appendix A are the primary goal of this report and are merely summarized on a comparative basis in figures 10-13. Appendix B shows a similar summary which presents the results from tables 2 and 3 in a graphical format for each adhesive.

The apparent shear strength and shear modulus indicated a significant decrease as the adhesives were exposed to heat and moisture. The environmental effects on these two adhesive properties follow the general trend, RTD > ETD > ETW, which was observed in previous experimental data [4].

Some of the shear modulus results were not reported, due to excessive vibration in extensometer data; consequently, additional specimens were tested. The following sections summarize the results for film and paste adhesives.

6.1 FILM ADHESIVES.

Panels for AF 126, EA 9628, FM 73, and FM 300 were fabricated with spacers to provide an even thickness distribution. For the thick bond lines, the use of spacers is imperative to obtain a uniform baseline. Except for FM 73 (RTD) where the strengths were equal, thinner bond lines produced higher shear strength results than thicker bond lines. This agrees with the data presented in reference 4. When compared to RTD conditions, the shear strength of EA 9628 film adhesives had the least reduction (8.7%) at ETD, while the shear modulus of EA 9695 had the least reduction (17.6%) at ETD. The FM 300 adhesive system performed better at both ETD and ETW conditions compared to others selected in this investigation. In addition, the shear strength of FM 300 at RTD conditions was the highest (6.8 ksi), and the shear modulus was 0.142 Msi.

Shear strength and modulus results for FM 73 were among the lowest test values obtained in this investigation. Even though AF 126 had higher values under RTD conditions, it had the lowest test results under ETD and ETW conditions. Compared to RTD conditions, shear strength of AF 126 under RTD and ETW conditions dropped 38.4% and 80.2%, respectively. The shear modulus of AF 126 under ETD and ETW conditions also dropped 82.3% and 98%, respectively.

As bond line thickness increased, failure modes indicated greater adhesive failure and a significant drop in apparent shear strength for all environmental conditions. EA 9628 failure modes were mostly cohesive and not significantly affected by bond line thickness or environmental conditions.

6.2 PASTE ADHESIVES.

Except under ETD conditions, EA 9394 shear strength and modulus were the highest among paste adhesives. In addition, this adhesive had the highest retention (with respect to RTD) under ETD conditions. The shear strength of EA 9392 had the highest retention (with respect to RTD) under ETW condition.

TABLE 2. AVERAGE SHEAR STRENGTH AND SHEAR MODULUS FOR FILM ADHESIVES

		RTD			ETD			ETW	
Adhesive Name	Avg. Bond line Thickness (in)	Panel Number	Strength (ksi)	Modulus (Msi)	Strength (ksi)	Modulus (Msi)	Strength (ksi)	Modulus (Msi)	
AF 126	0.013	1	6.5269	0.1241	4.0236	0.0246	1.4812	0.0069	
AF 126	0.042	2	5.3067	0.1152	3.5885	0.0244	0.9377	0.0023	
EA 9628	0.010	1	6.2105	0.1037	5.6730	**	4.2368	0.0471	
EA 9628	0.031	2	5.8553	0.1364	4.2792	0.0664	3.7153	0.0534	
EA 9695	0.011	1	6.4816	0.1416	5.4993	0.0811	5.3412	0.0788	
EA 9695	0.034	2	5.9497	0.1332	4.9712	0.0810	4.7314	0.0804	
EA 9696	0.011		6.7582	0.1179	5.5199	0.0564	4.7151	0.0427	
FM 300	0.014	1	6.8042	0.1150	5.3061	0.0836	5.0003	0.0826	
FM 300	0.033	2	6.7260	0.1278	4.6795	0.0841	4.4569	0.0796	
FM 73	0.019	1	4.9333	0.0878	3.5780	0.0322	2.4119	0.0117	
FM 73	0.028	2	5.0695	0.0772	3.2015	0.0256	1.3772	0.0045	

NOTE: ** - Excessive vibration in extensometer data

TABLE 3. AVERAGE SHEAR STRENGTH AND SHEAR MODULUS FOR PASTE ADHESIVES

Adhesive Name	Avg. Bond line Thickness	Cure Cycle	Panel Number	RTD			ETD			ETW	
				Strength (ksi)	Modulus (Msi)	Strength (ksi)	Strength (ksi)	Modulus (Msi)	Strength (ksi)	Modulus (Msi)	Modulus (Msi)
EA 9309.3 NA	0.040			4.2210	0.0932	0.9552		**	0.6597	0.0009	
EA 9346.5	0.044			5.5158	0.1043	4.1499		0.0533	3.1779	0.0478	
EA 9359.3	0.032	1		3.2716	0.0809	0.9163		0.0308	0.7266	0.0130	
EA 9359.3	0.038	2		4.3699	0.1145	1.6552		0.0306	1.1979	0.0157	
EA 9360	0.036	1	1	4.8613	0.0921	2.6326		0.0484	1.7773	0.0423	
EA 9360	0.032	1	2	3.8758	0.0918	2.0457		0.0510	1.7826	0.0430	
EA 9360	0.051	2	2	4.0690	0.1053	2.3427		0.0568	1.7702	0.0535	
EA 9392	0.033	1		5.6257	0.0982	2.6520		0.0668	3.0793	0.0598	
EA 9392	0.042	2		5.5889	0.1500	3.4632		0.0924	3.7709	0.0775	
EA 9394	0.042			6.1555	0.1753	3.5653		0.1353	4.0856	0.0987	
EA 9396	0.034			4.2492	0.1012	2.4954		**	1.8653	0.0589	
MGS L418	0.056			1.7477	0.0571	1.0173		0.0409	1.0221	0.0419	
PTM&W ES 6292	0.052			3.6775	0.1009	2.0225		0.0717	1.7139	0.0690	
3M DP-460 EG	0.045			4.3208	0.0954	0.4400		**	1.3404	0.0011	
3M DP-460 NS	0.040			4.5518	0.1133	0.6100		0.0008	0.8630	0.0010	
3M DP-820	0.051			3.7343	0.0866	1.0998		**	0.7280	0.0202	

NOTE: ** - Excessive vibration in extensometer data

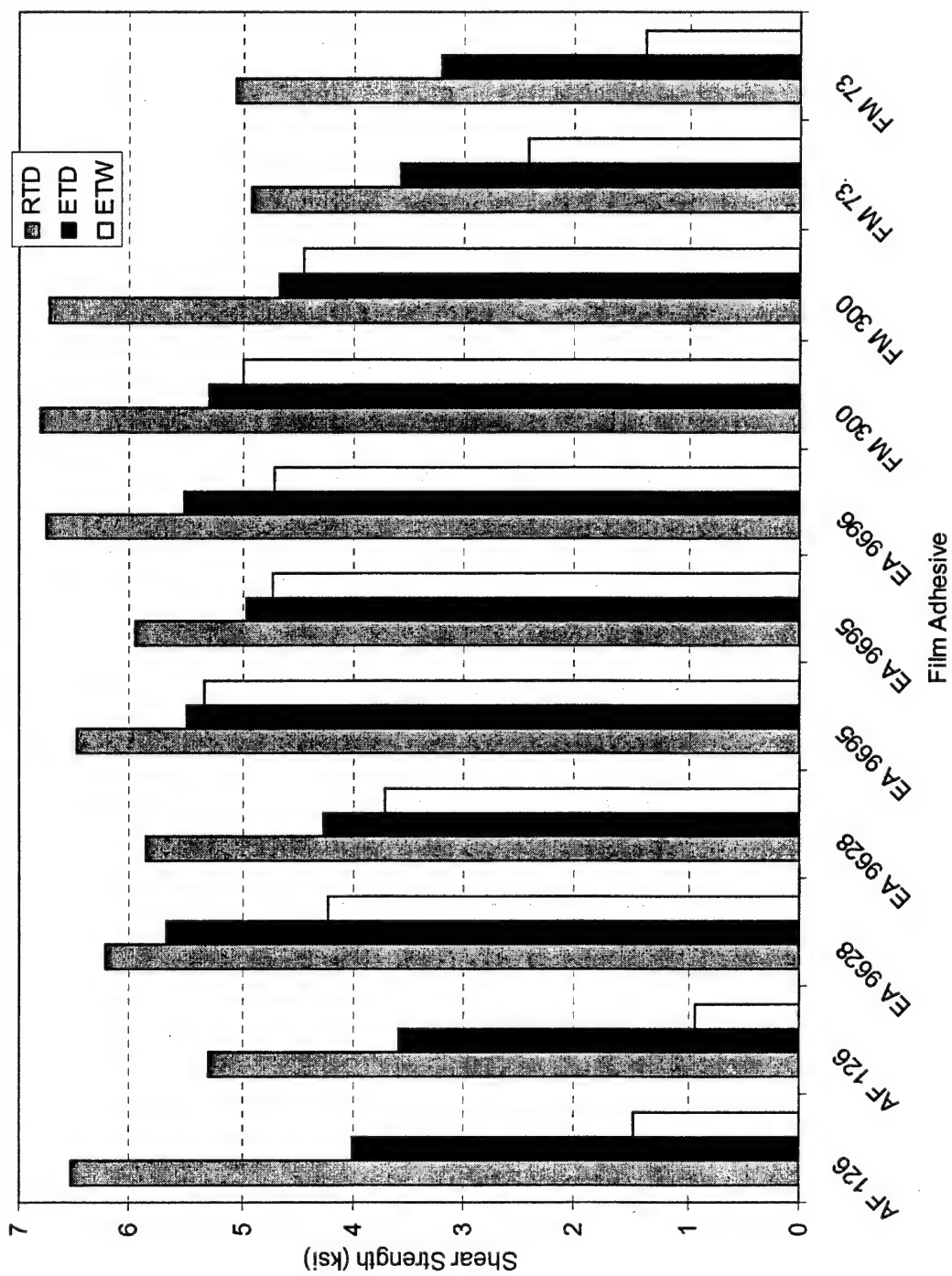


FIGURE 10. ENVIRONMENTAL EFFECTS ON SHEAR STRENGTH OF FILM ADHESIVES

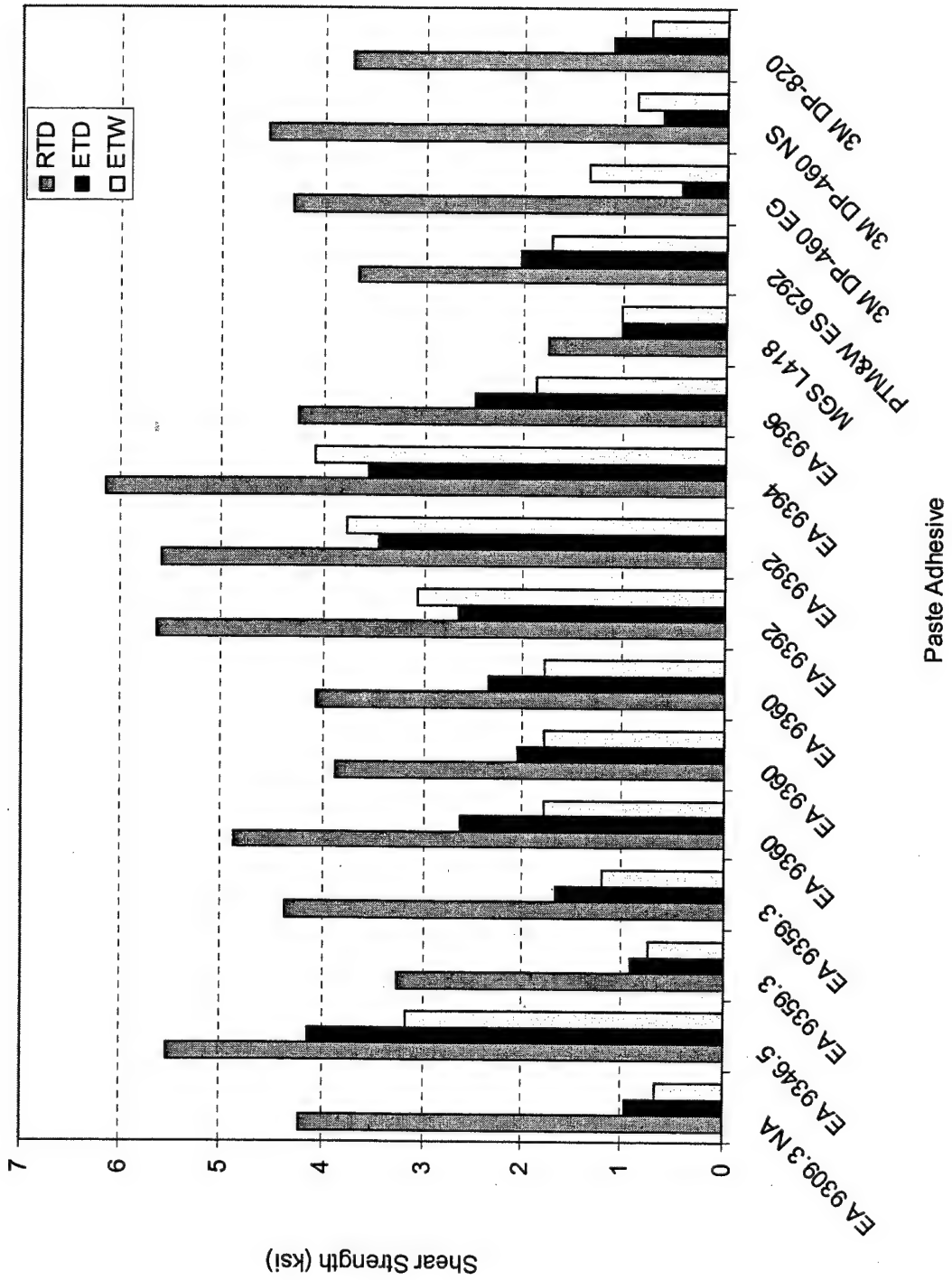


FIGURE 11. ENVIRONMENTAL EFFECTS ON SHEAR STRENGTH OF PASTE ADHESIVES

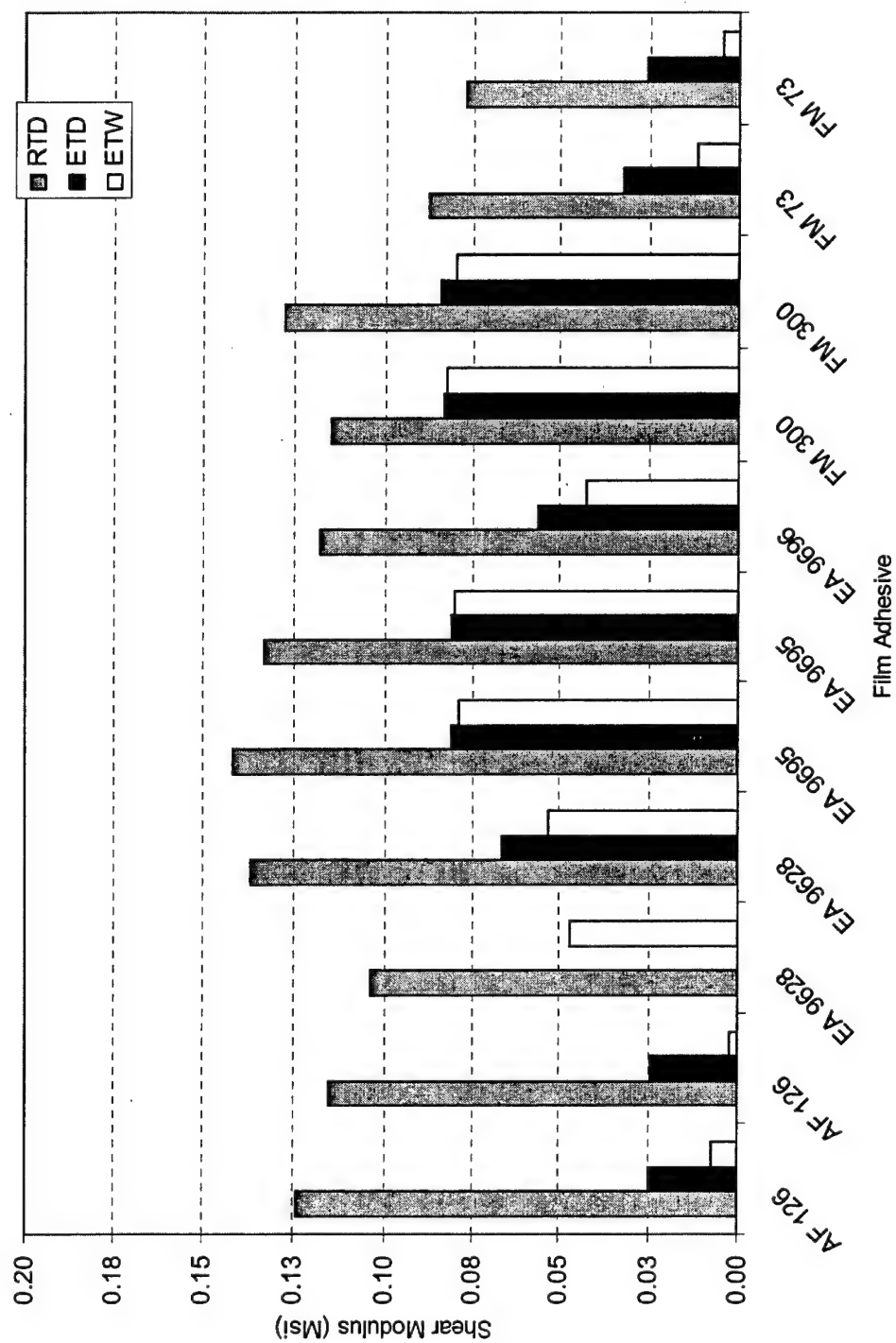


FIGURE 12. ENVIRONMENTAL EFFECTS ON SHEAR MODULUS OF FILM ADHESIVES

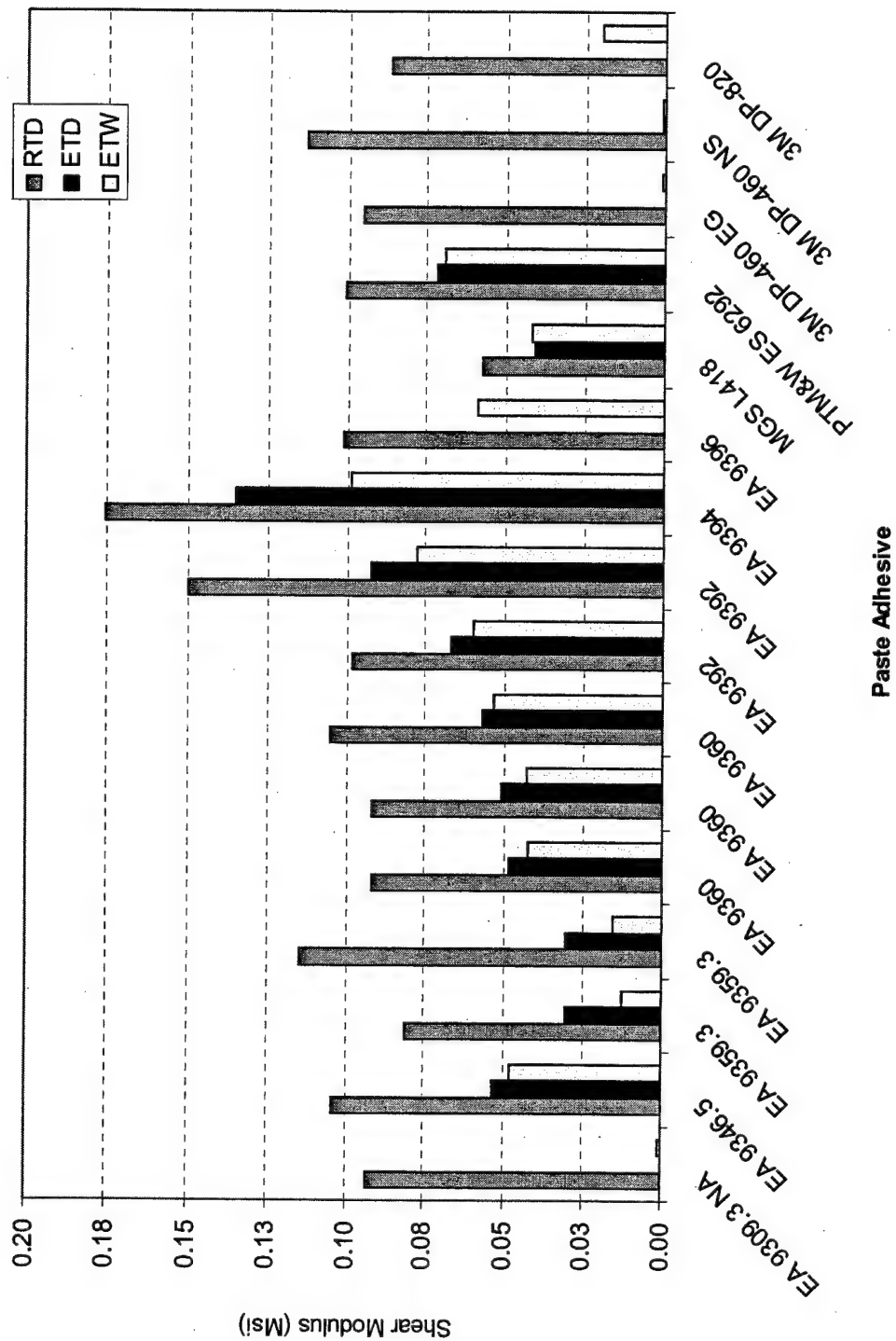


FIGURE 13. ENVIRONMENTAL EFFECTS ON SHEAR MODULUS OF PASTE ADHESIVES

Compared to the results for RTD conditions, average shear strength and modulus for 3M DP-460EG, DP-460NS, DP-820, and EA 9309.3NA indicated a significant drop under ETD and ETW conditions, ranging from 70.5% to 84.4%, while the shear modulus drop ranged from 76.6% to 99.1%. At elevated temperatures, these adhesives indicated highly plastic behavior and caused scatter in the extensometer data. In addition, they indicated significantly high-shear deformation at elevated temperatures (appendix A).

The additional 48-hour ambient cure for EA 9360, EA 9392, and EA 9359.3 paste adhesives improved apparent shear strength and shear modulus at ETD and ETW conditions. The apparent shear strength and shear modulus of EA 9359.3 at RTD was improved by 33.6% and 41.6%, respectively, for the second cure cycle. In addition, the shear modulus of EA 9392 was improved by 52.8% for the second cure cycle.

6.3 FAILURE MODES.

Failure modes of the specimen were found to be strongly dependent on the adhesives' ductility at different environments. Appendix C shows the failure mode of each specimen at RTD, ETD, and ETW conditions. Figures C-1 through C-3 show that the failure modes of some adhesives did not change with respect to the environment. However, for the same environment there were a few cases where the failure mode did change. The apparent shear strength of each of these incidents indicated significant change due to different failure modes.

7. SUMMARY.

This report provides shear stress-strain data for several structural adhesive systems used in industry. In addition to ambient conditions, these adhesive systems were also characterized in elevated temperature and moisture conditions. The primary purpose of this report was to make this data available for use in the industry for design and analysis of bonded joints.

The test data generated in this study shows that adhesives become weak and ductile at high temperatures and brittle at low temperatures. In general, the yield stress and modulus of all adhesives decrease with increasing temperature. The plastic behavior of adhesives at elevated temperatures caused scatter in extensometer data and significant shear deformation. Additionally, mechanical properties of adhesives were degraded by the absorption of moisture from humid environmental conditions due to either water diffusion to the adhesive or water migration to the adhesive-adherend interface.

8. REFERENCES.

1. ASTM D 5656—Standard Test Method for Thick-Adherend Metal Lap-Shear Joints for Determination of the Stress-Strain Behavior of Adhesives in Shear by Tension Loading, *Annual Book of ASTM Standards*, 1997, Vol. 15.06, pp. 470-475.
2. Bonded Joints, MIL-HDBK-17-1E, Working Draft, pp. 7-44 – 7-62.
3. Krieger Jr., R. B., "Stress Analysis Concepts for Adhesive Bonding of Aircraft Primary Structure," *Adhesively Bonded Joints: Testing, Analysis, and Design*, ASTM STP 981,

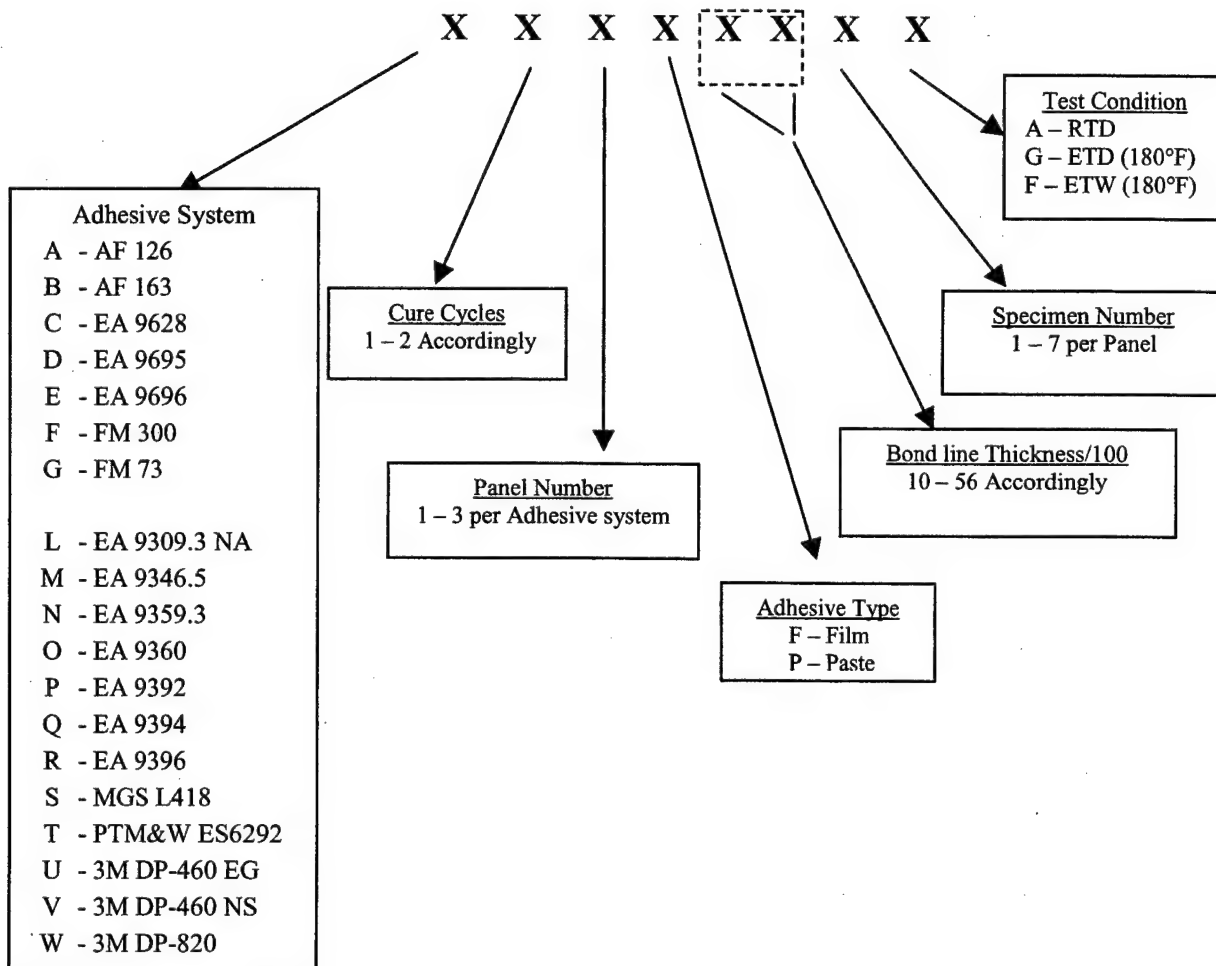
W.S. Johnson, ed., American Society for Testing and Materials, Philadelphia Pennsylvania, 1988, pp. 264-275.

4. Tomblin, J., Yang, C., and Harter, P., "Investigation of Thick Bond line Adhesive Joints," DOT/FAA/AR-01/33, FAA William J. Hughes Technical Center, Atlantic City International Airport, NJ, July 2001.
5. Tomblin, J., Harter, P., Seneviratne W., and Yang, C., "Characterization of Bond line Thickness Effects in Adhesive Joints," *ASTM Journal of Testing and Evaluation*, JCTRE, Vol. 24, No. 2, April 2002, pp. 332-344.
6. Yang, C., Huang, H., and Tomblin, J., "Evaluation and Adjustments for ASTM D 5656—Standard Test Method for Thick Adherend Metal Lap Shear Joints for Determination of Stress-Strain Behavior of Adhesives in Shear by Tension Loading," *ASTM Journal of Testing and Evaluation*, JTEVA, Vol. 29, No.1, January 2001, pp. 36-43.

APPENDIX A—CHARACTERISTIC SHEAR RESPONSES

Characteristic shear responses of various structural adhesives are shown in this section. Curves were truncated at the shear strain of 0.3 radians for more clarity and focus on the initial region of the response. Therefore, the apparent shear strength presented in tables 2 and 3 may actually be more than depicted in the plots shown in appendix A.

Figure 5 is repeated here for clarity and ease of using the plots in appendix A. Note that the last letter in the code represents the environment in which the response was measured.



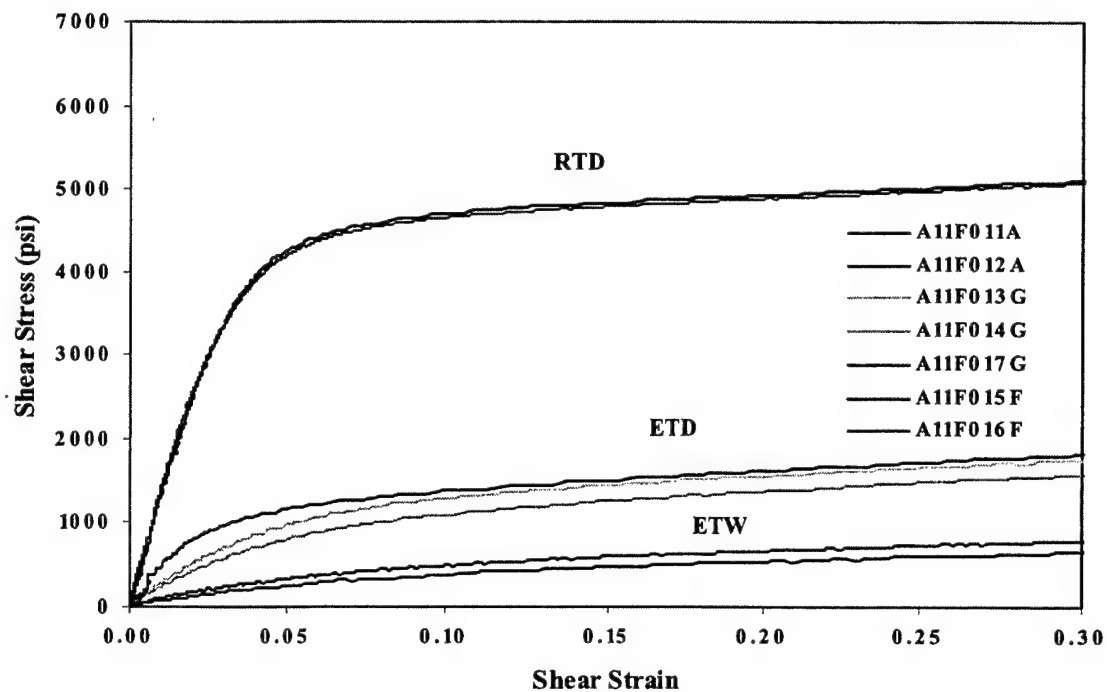


FIGURE A-1. CHARACTERISTIC SHEAR RESPONSE OF AF 126 FILM ADHESIVE (BOND LINE = 0.013") WITH RESPECT TO THE ENVIRONMENT

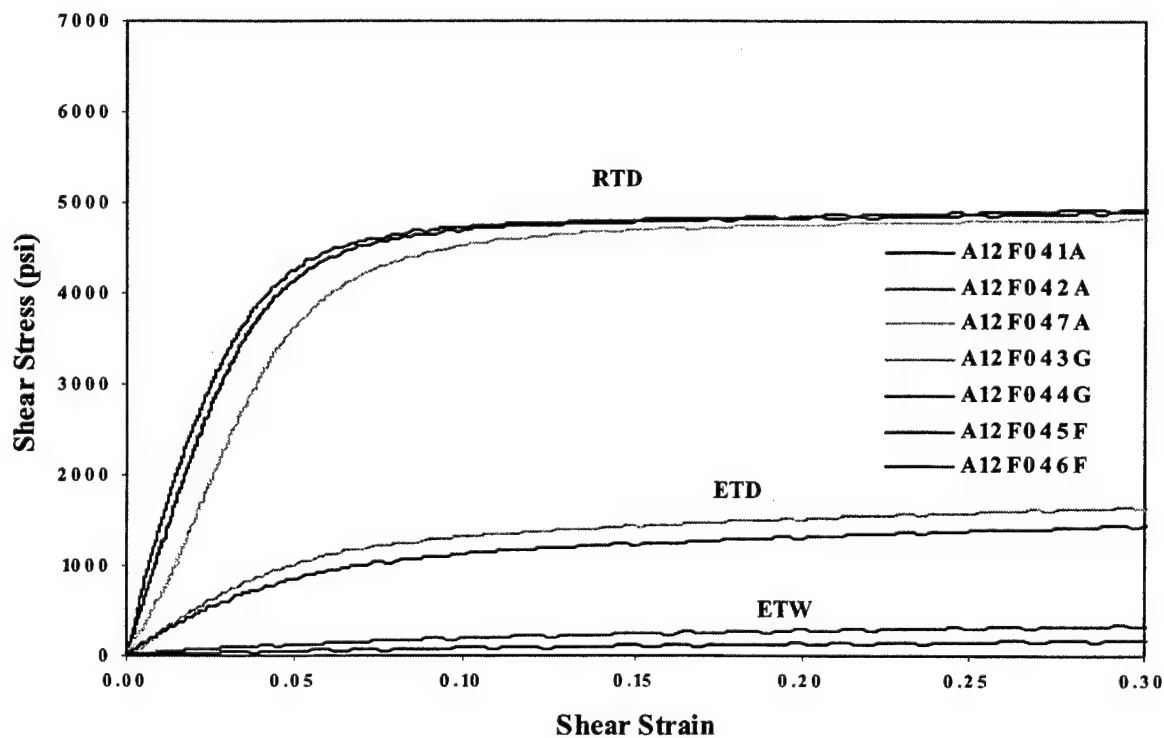


FIGURE A-2. CHARACTERISTIC SHEAR RESPONSE OF AF 126 FILM ADHESIVE (BOND LINE = 0.042") WITH RESPECT TO THE ENVIRONMENT

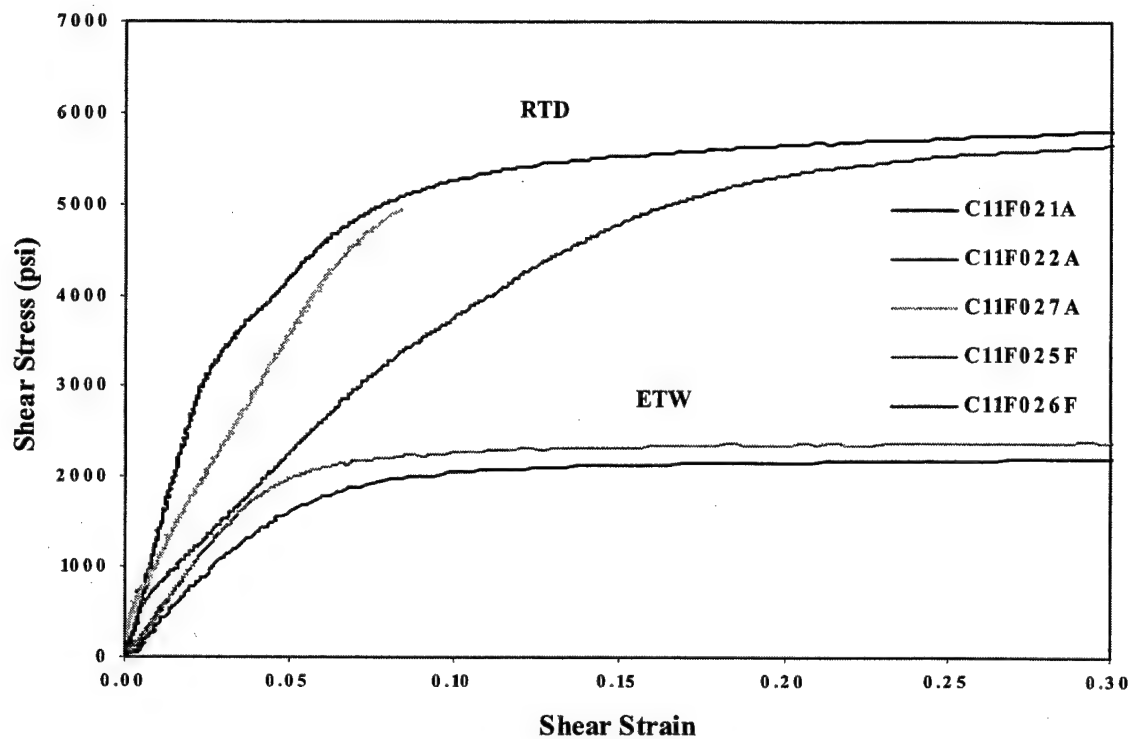


FIGURE A-3. CHARACTERISTIC SHEAR RESPONSE OF EA 9628 FILM ADHESIVE (BOND LINE = 0.010") WITH RESPECT TO THE ENVIRONMENT

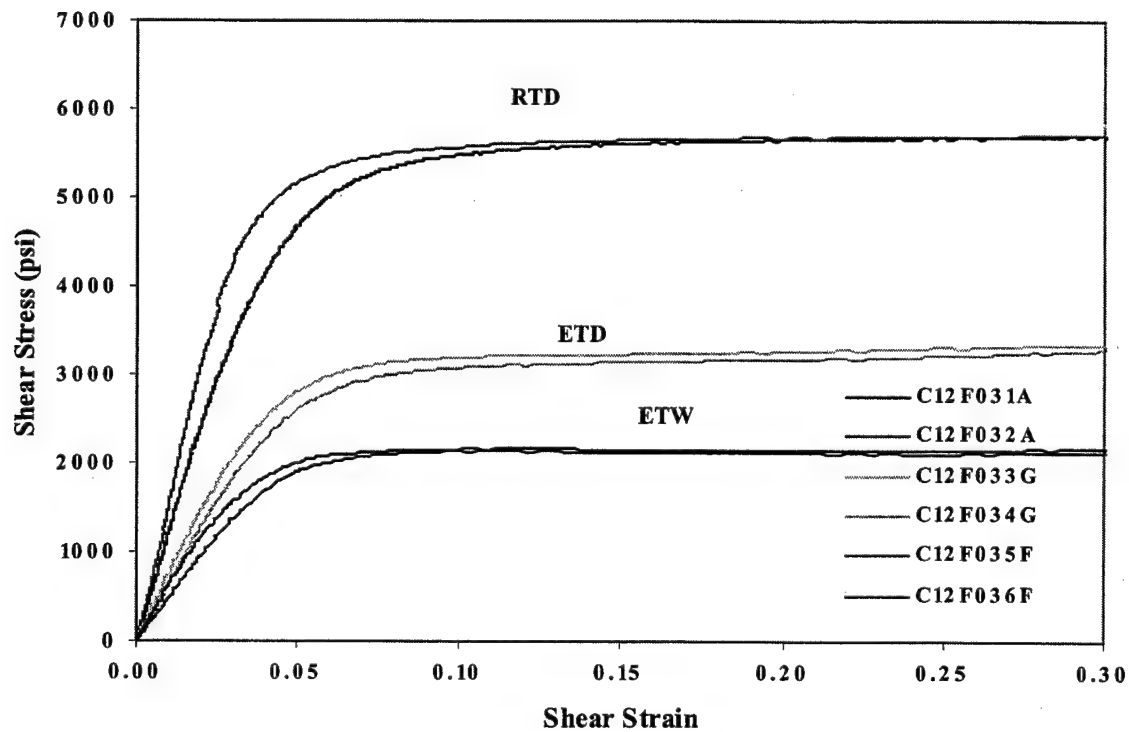


FIGURE A-4. CHARACTERISTIC SHEAR RESPONSE OF EA 9628 FILM ADHESIVE (BOND LINE = 0.031") WITH RESPECT TO THE ENVIRONMENT

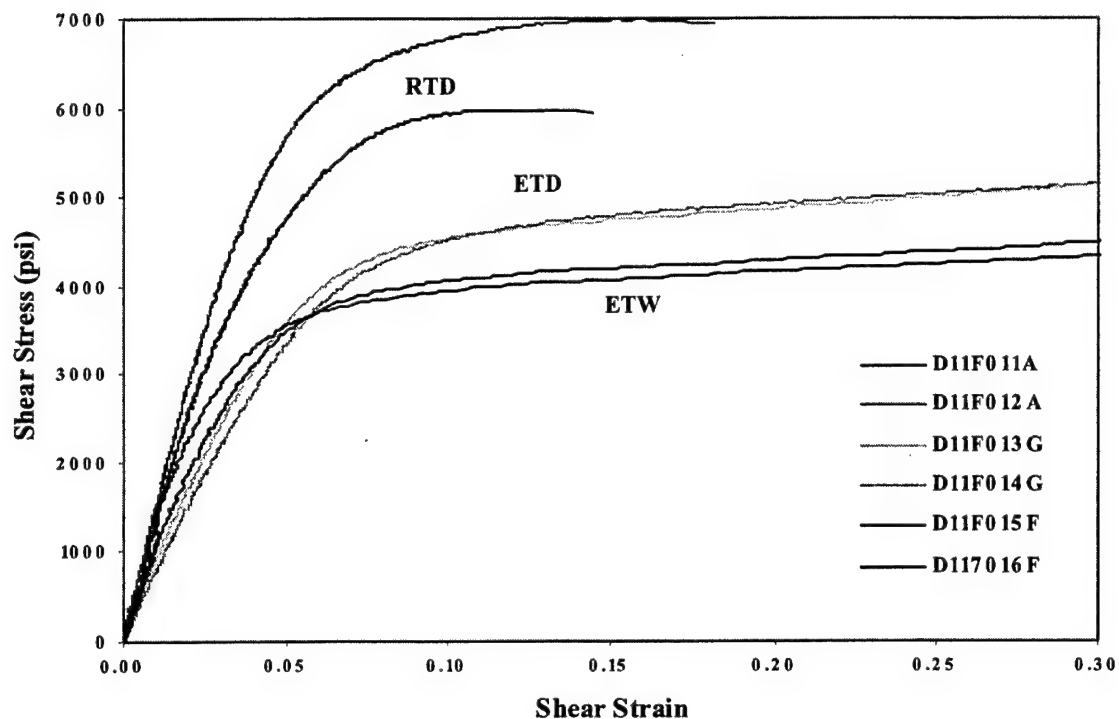


FIGURE A-5. CHARACTERISTIC SHEAR RESPONSE OF EA 9695 FILM ADHESIVE (BOND LINE = 0.011") WITH RESPECT TO THE ENVIRONMENT

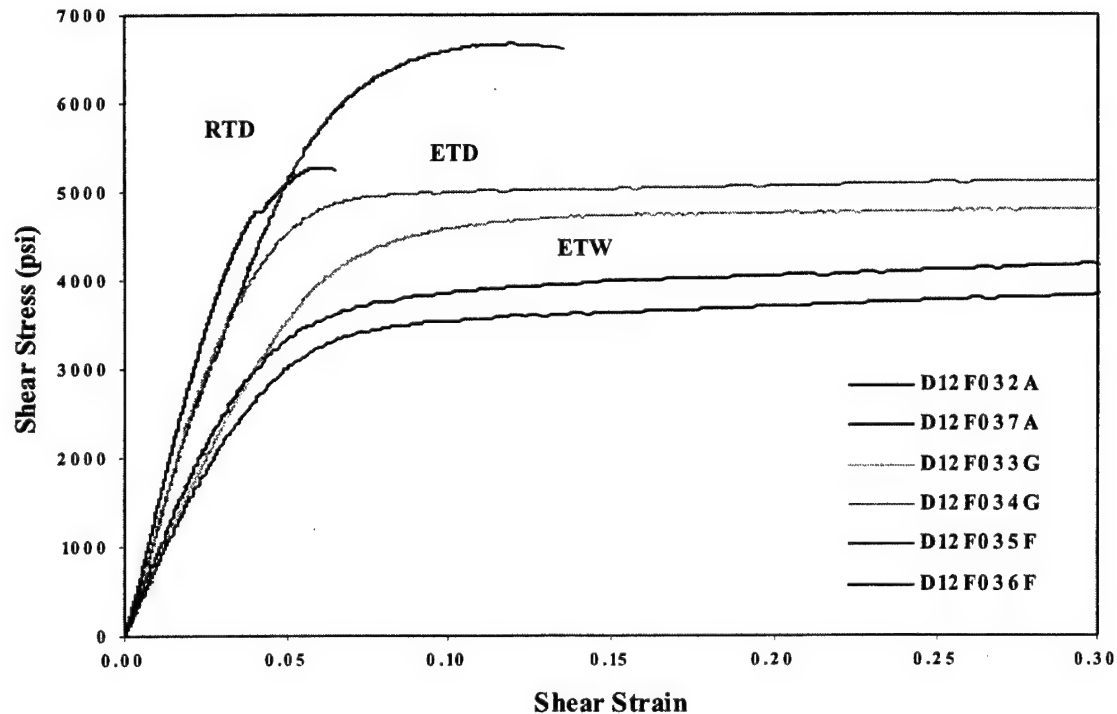


FIGURE A-6. CHARACTERISTIC SHEAR RESPONSE OF EA 9695 FILM ADHESIVE (BOND LINE = 0.034") WITH RESPECT TO THE ENVIRONMENT

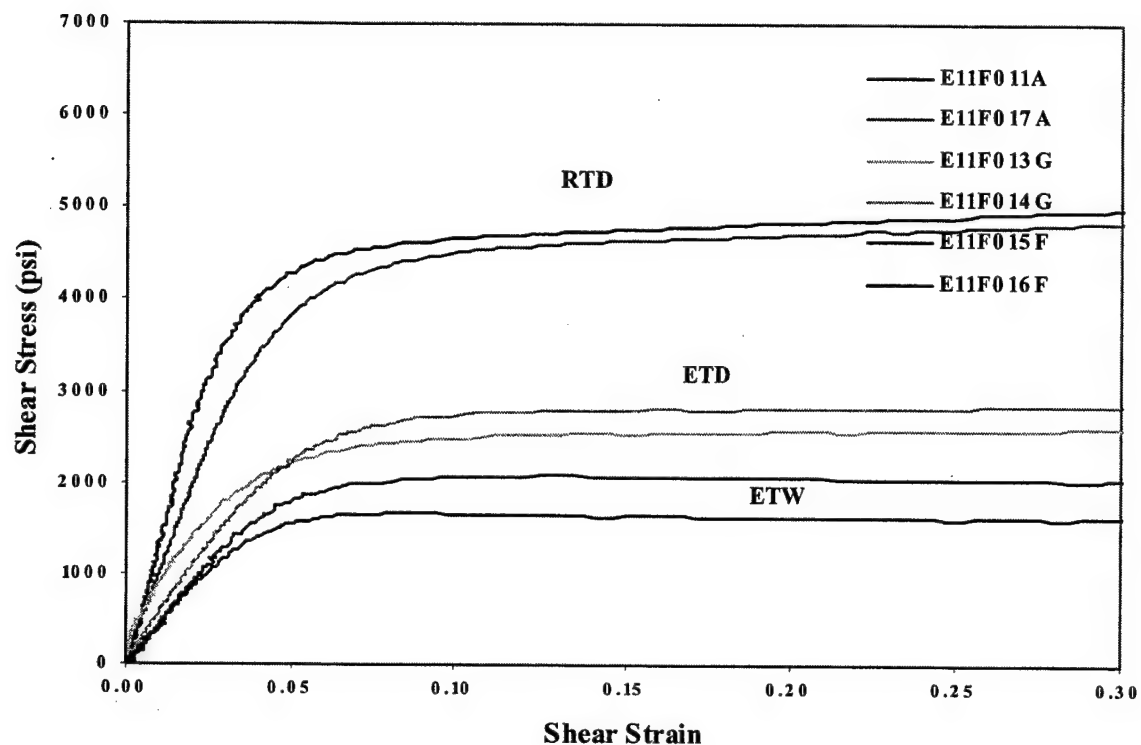


FIGURE A-7. CHARACTERISTIC SHEAR RESPONSE OF EA 9696 FILM ADHESIVE (BOND LINE = 0.011") WITH RESPECT TO THE ENVIRONMENT

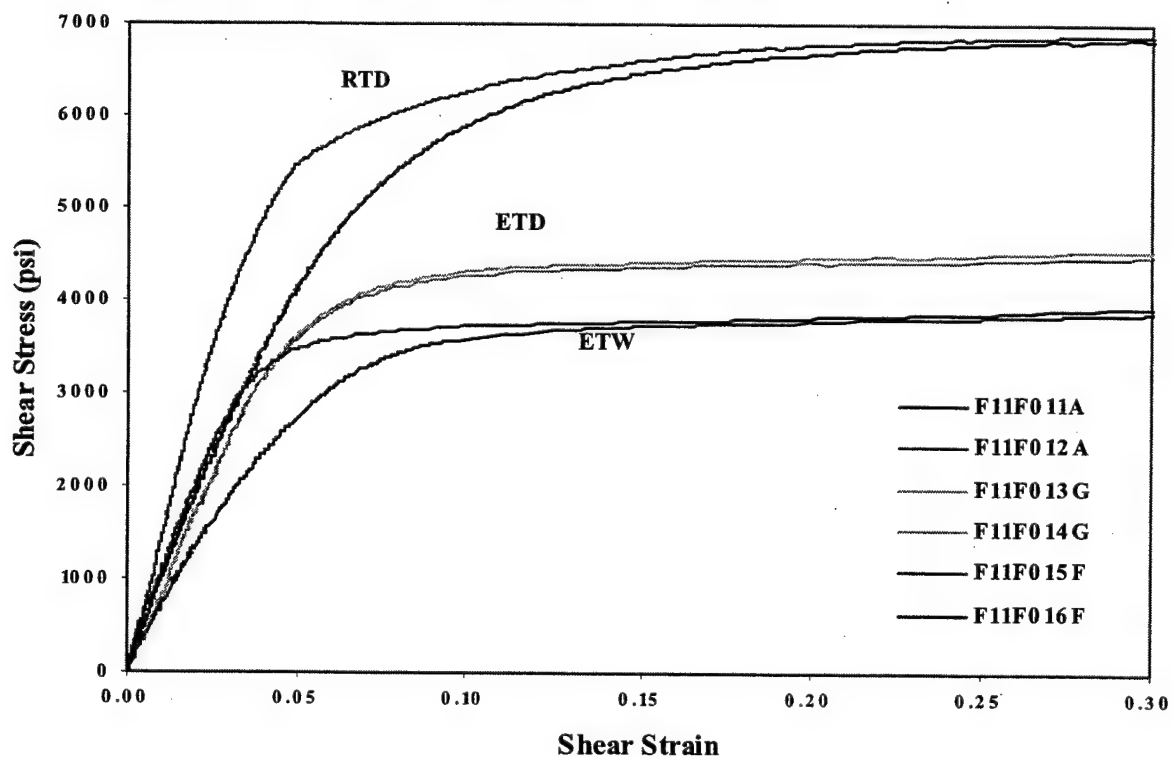


FIGURE A-8. CHARACTERISTIC SHEAR RESPONSE OF FM 300 FILM ADHESIVE (BOND LINE = 0.014") WITH RESPECT TO THE ENVIRONMENT

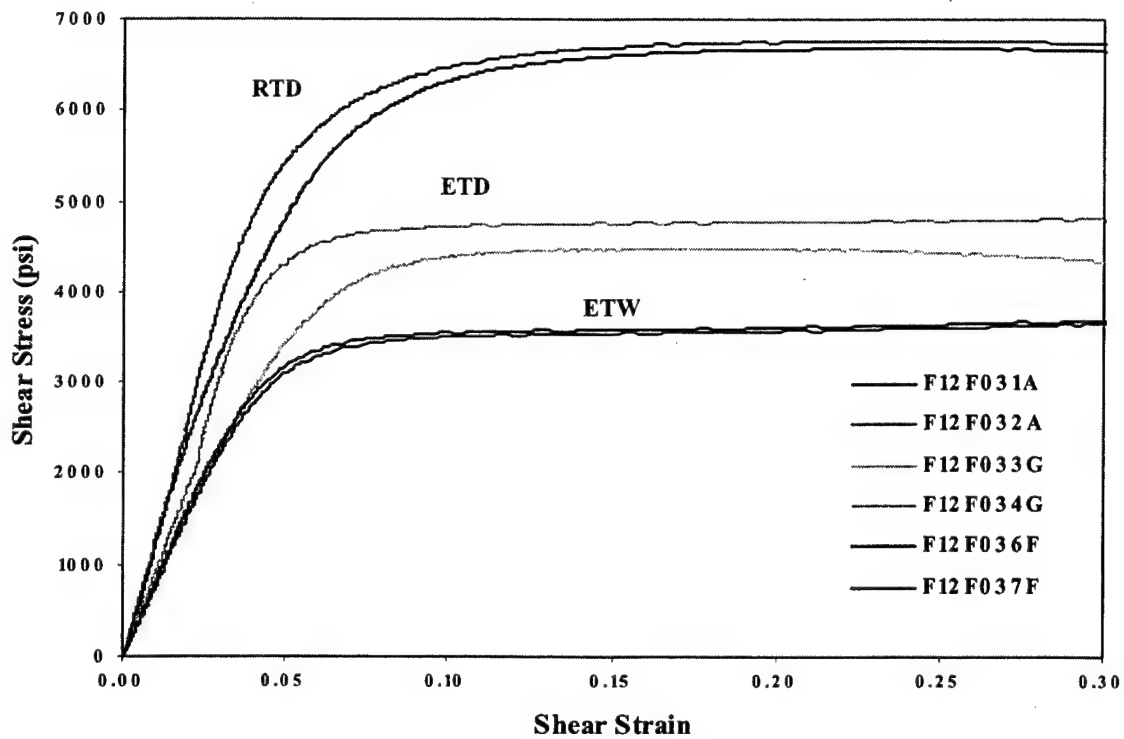


FIGURE A-9. CHARACTERISTIC SHEAR RESPONSE OF FM 300 FILM ADHESIVE (BOND LINE = 0.033") WITH RESPECT TO THE ENVIRONMENT

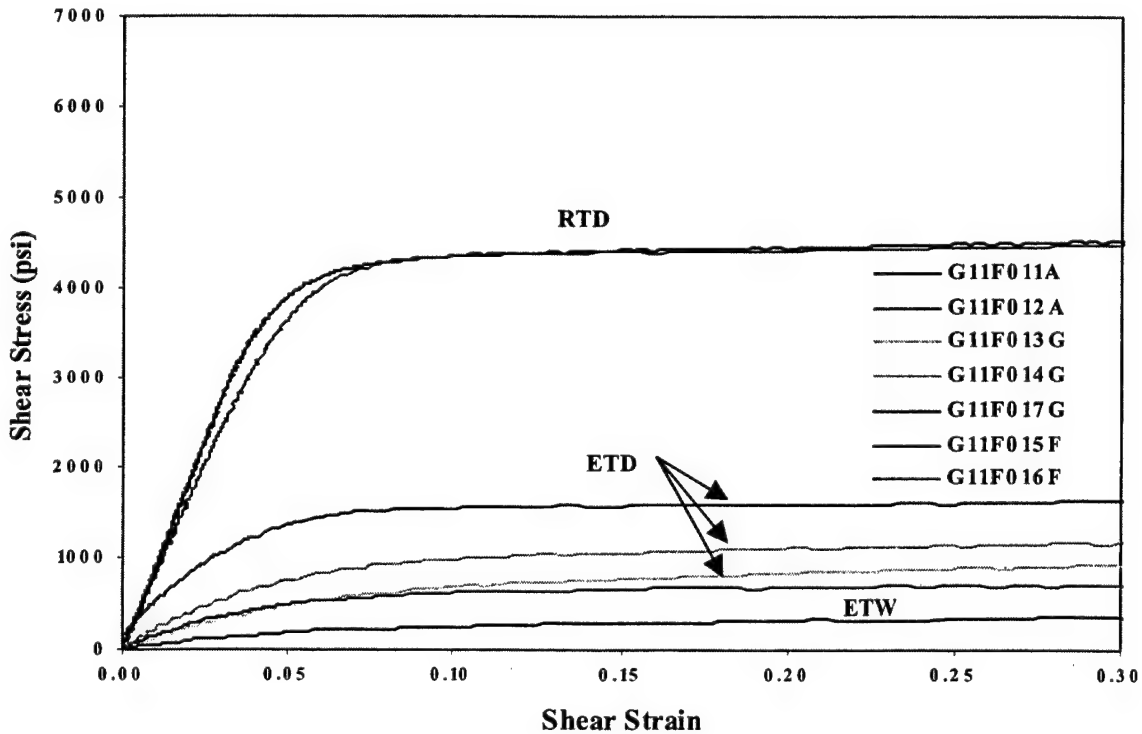


FIGURE A-10. CHARACTERISTIC SHEAR RESPONSE OF FM 300 FILM ADHESIVE (BOND LINE = 0.019") WITH RESPECT TO THE ENVIRONMENT

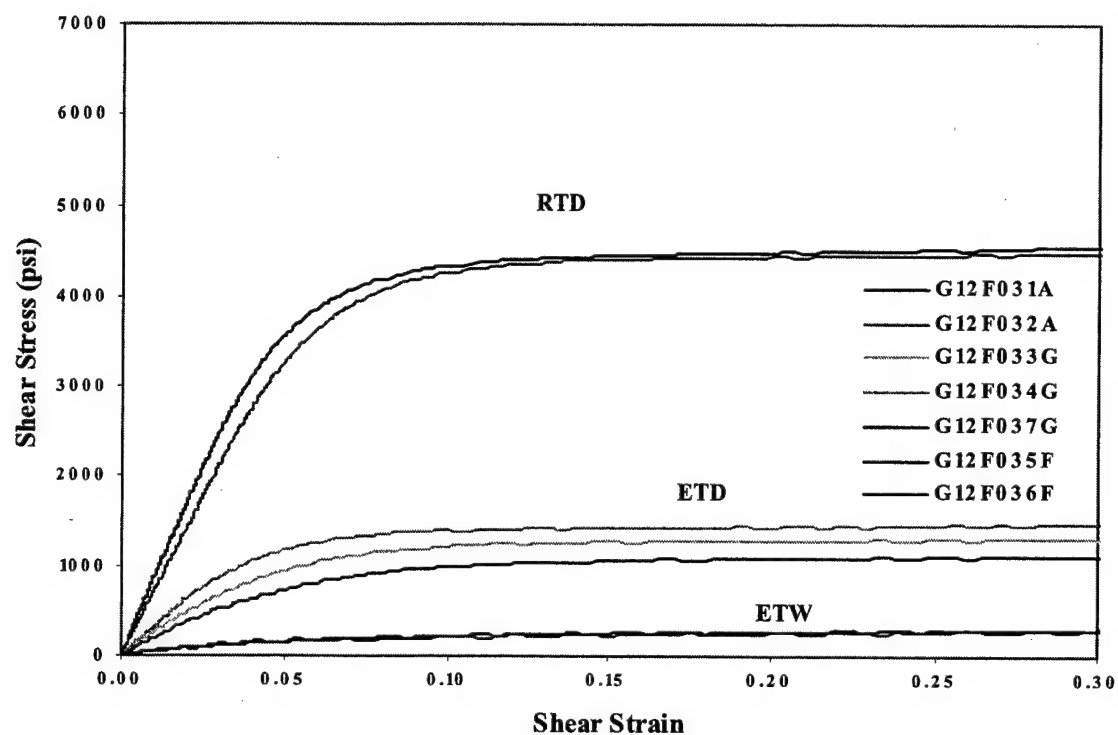


FIGURE A-11. CHARACTERISTIC SHEAR RESPONSE OF FM 300 FILM ADHESIVE (BOND LINE = 0.028") WITH RESPECT TO THE ENVIRONMENT

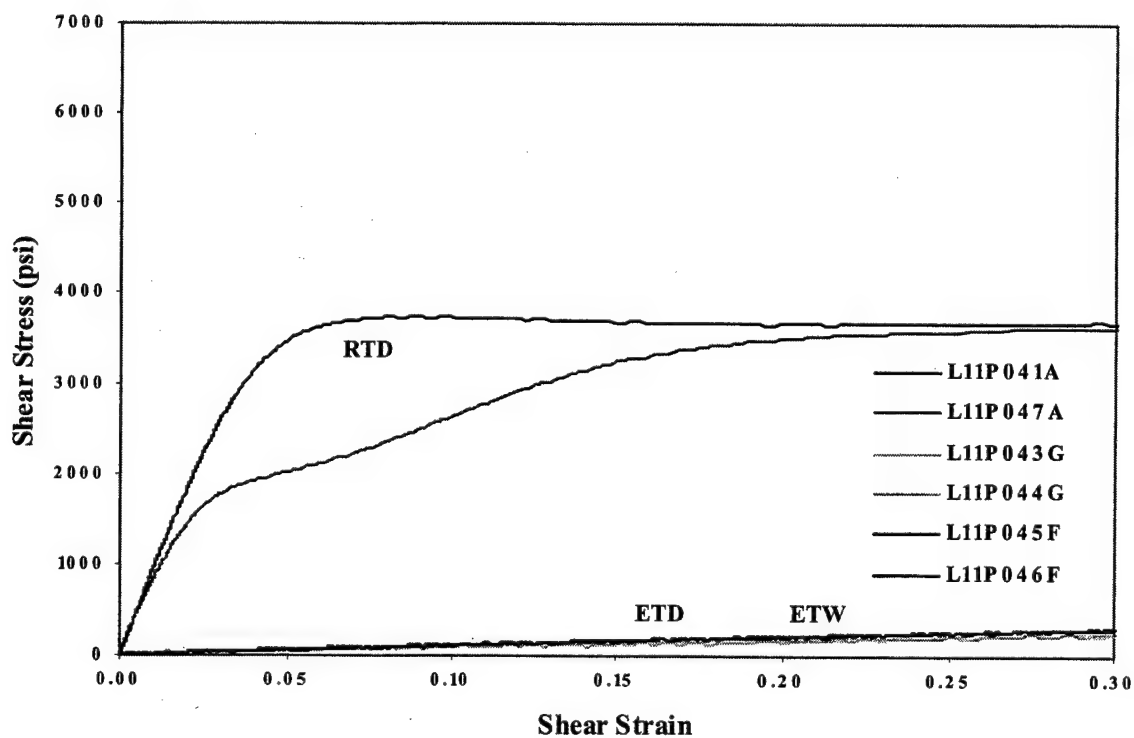


FIGURE A-12. CHARACTERISTIC SHEAR RESPONSE OF EA 9309.3NA PASTE ADHESIVE (BOND LINE = 0.040") WITH RESPECT TO THE ENVIRONMENT

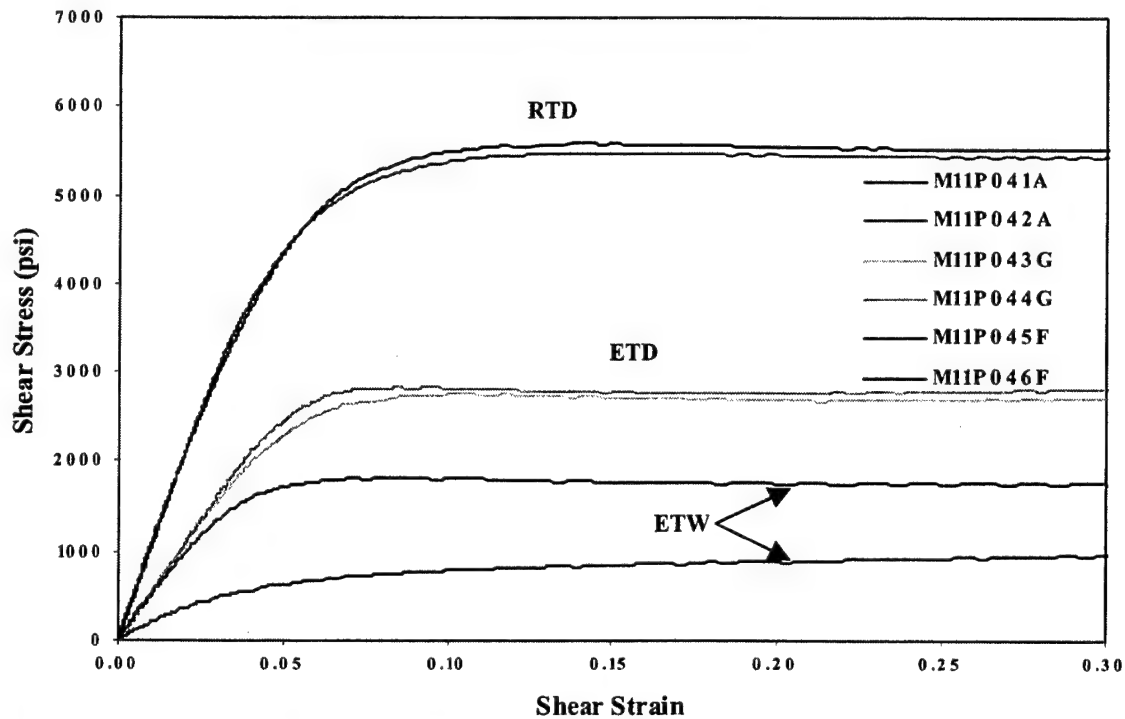


FIGURE A-13. CHARACTERISTIC SHEAR RESPONSE OF EA 9346.5 PASTE ADHESIVE (BOND LINE = 0.044") WITH RESPECT TO THE ENVIRONMENT

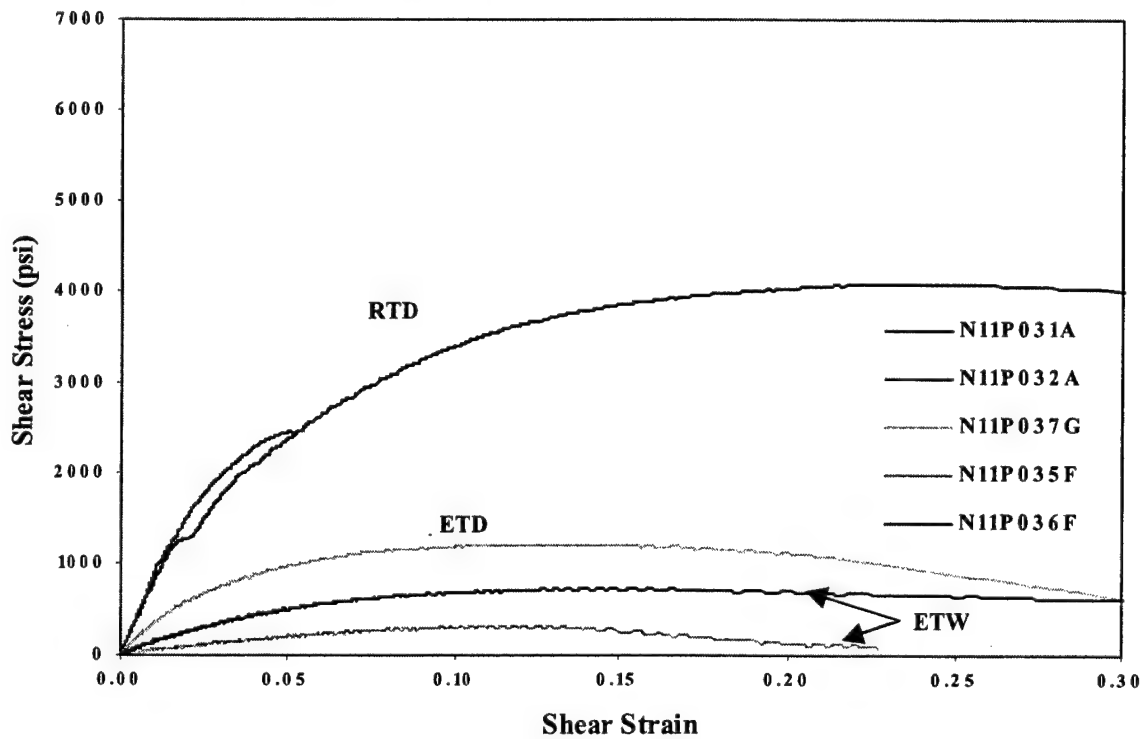


FIGURE A-14. CHARACTERISTIC SHEAR RESPONSE OF EA 9359.3 PASTE ADHESIVE (BOND LINE = 0.032") WITH RESPECT TO THE ENVIRONMENT

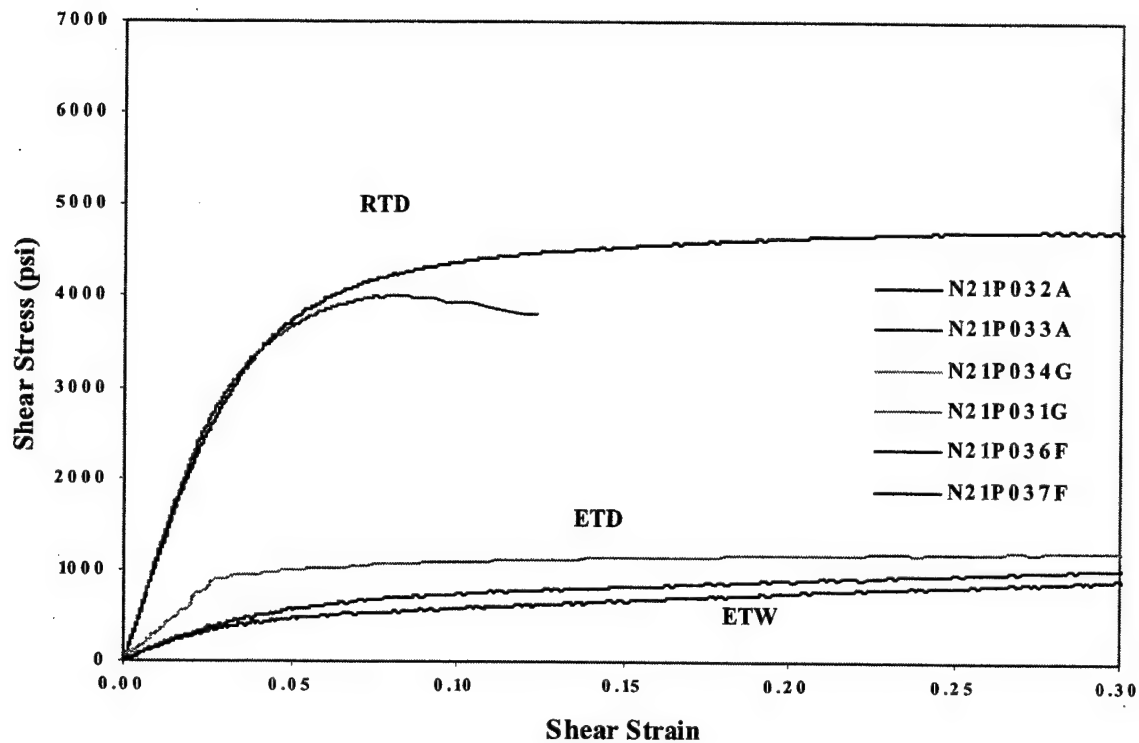


FIGURE A-15. CHARACTERISTIC SHEAR RESPONSE OF EA 9359.3 PASTE ADHESIVE (BOND LINE = 0.038") WITH RESPECT TO THE ENVIRONMENT

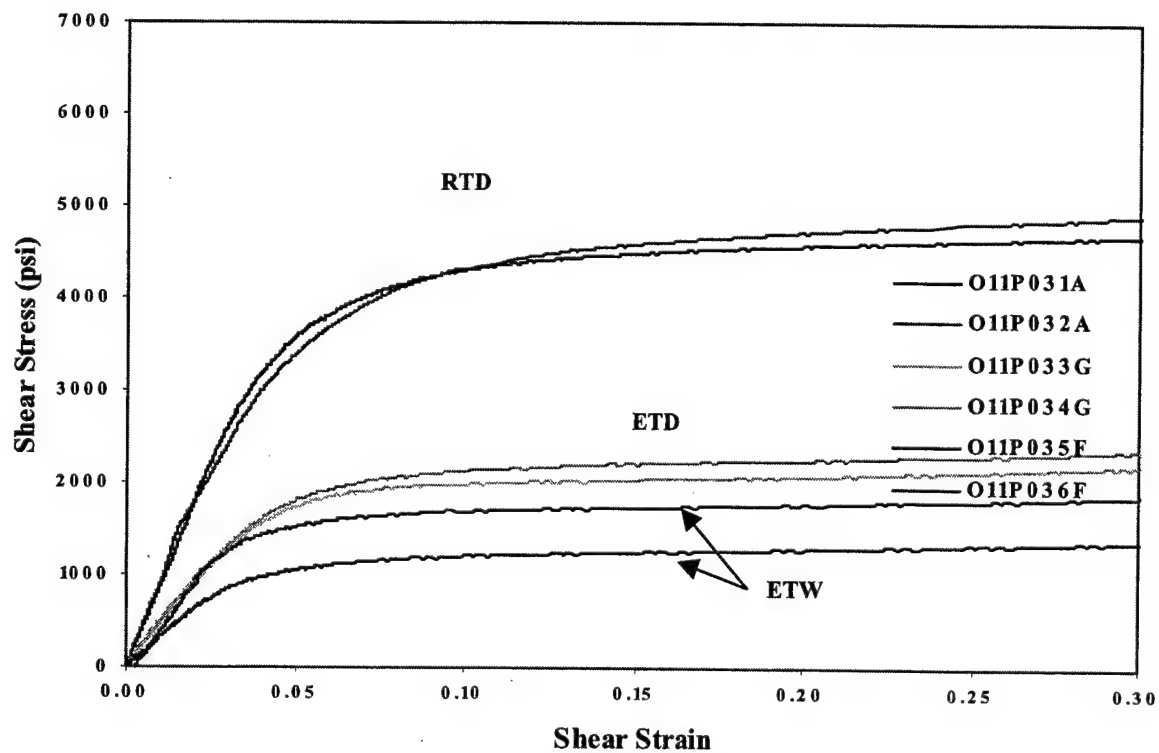


FIGURE A-16. CHARACTERISTIC SHEAR RESPONSE OF EA 9360 PASTE ADHESIVE (BOND LINE = 0.036") WITH RESPECT TO THE ENVIRONMENT

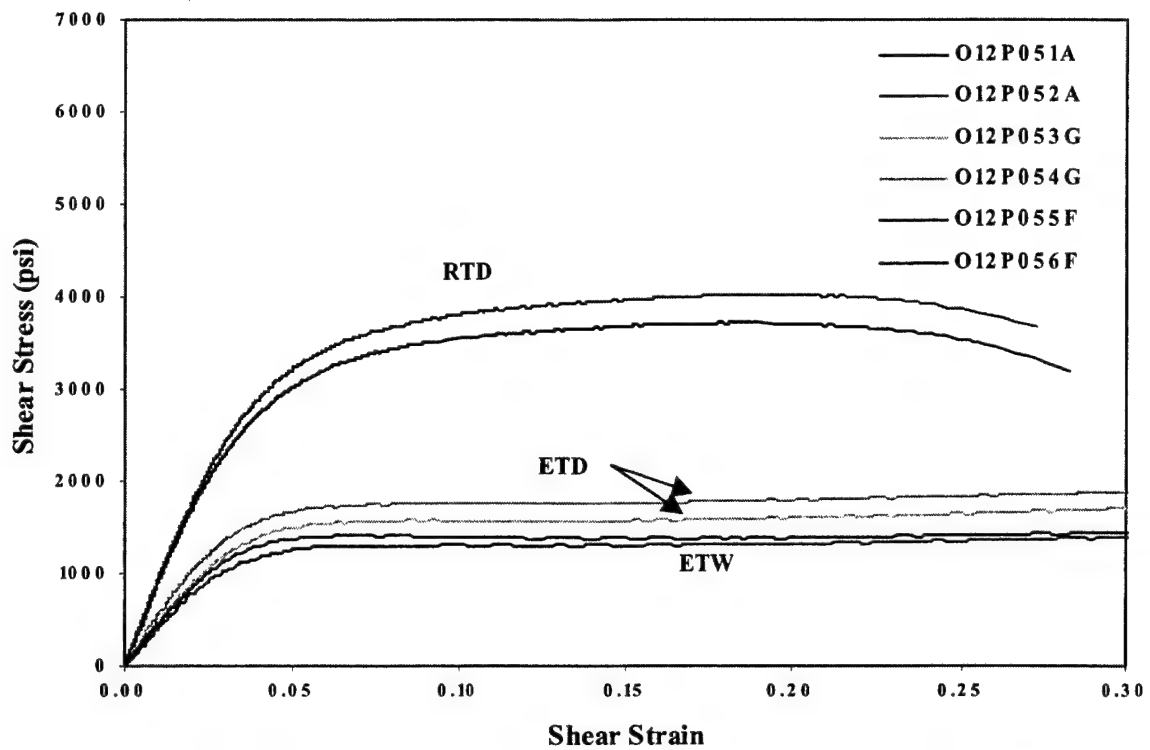


FIGURE A-17. CHARACTERISTIC SHEAR RESPONSE OF EA 9360 PASTE ADHESIVE (BOND LINE = 0.032") WITH RESPECT TO THE ENVIRONMENT

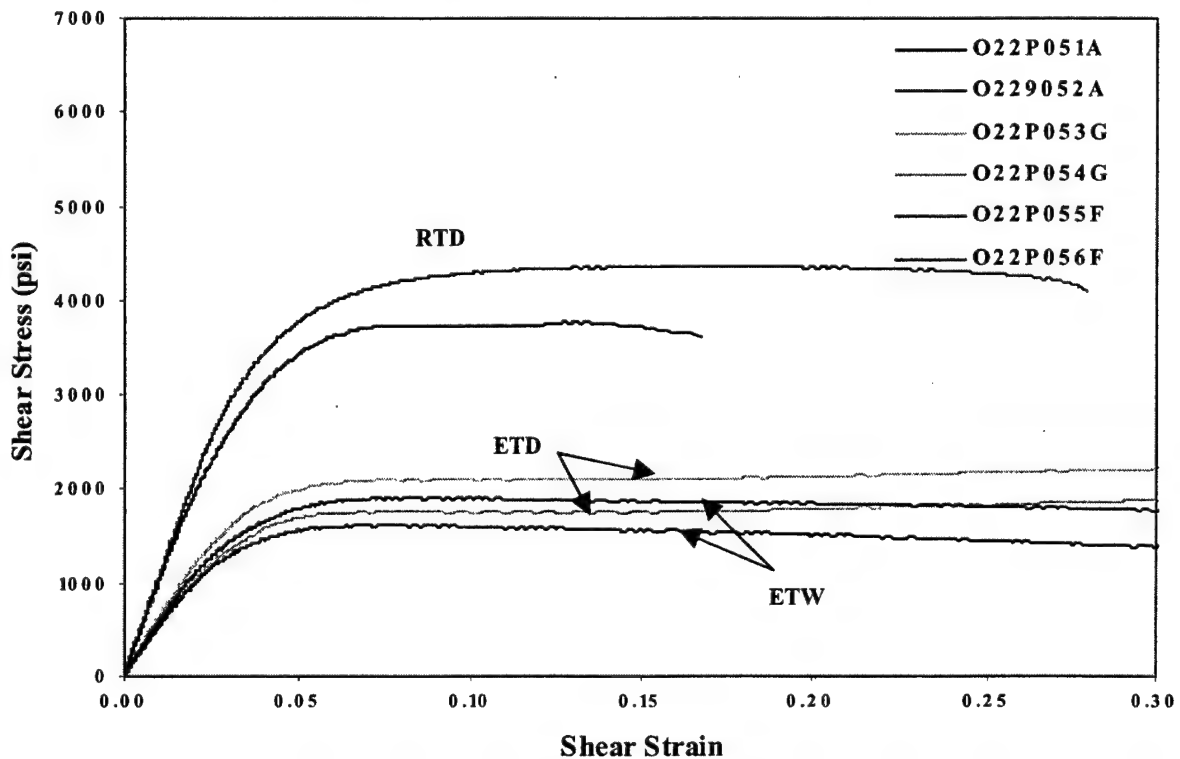


FIGURE A-18. CHARACTERISTIC SHEAR RESPONSE OF EA 9360 PASTE ADHESIVE (BOND LINE = 0.051") WITH RESPECT TO THE ENVIRONMENT

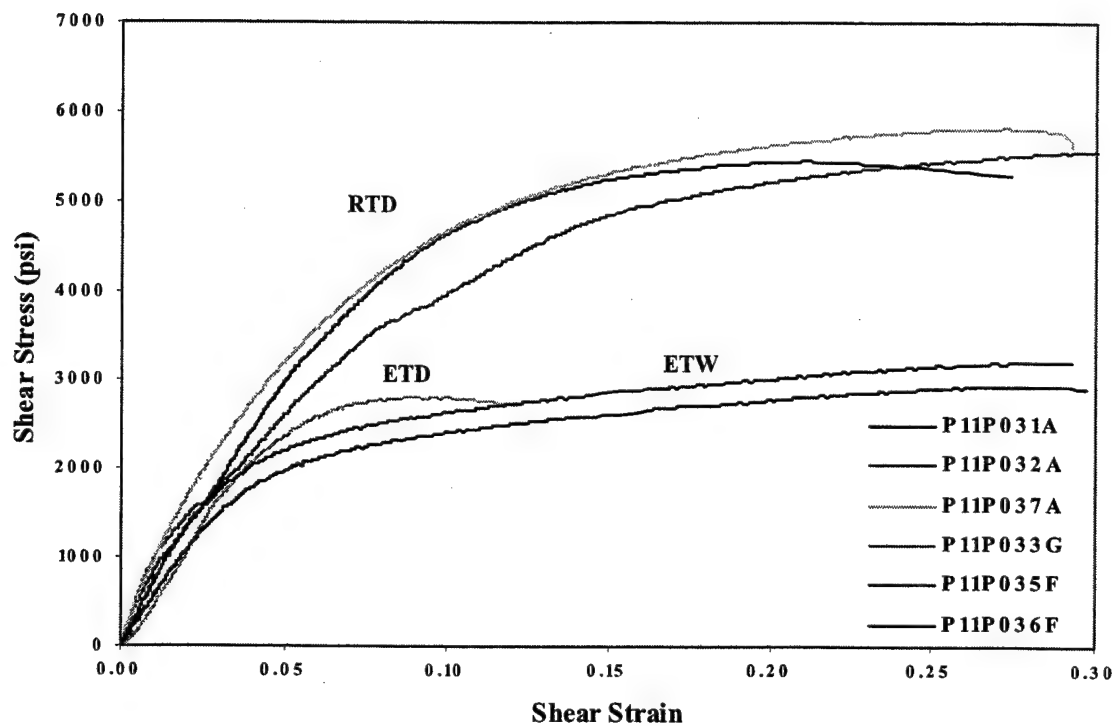


FIGURE A-19. CHARACTERISTIC SHEAR RESPONSE OF EA 9392 PASTE ADHESIVE (BOND LINE = 0.033") WITH RESPECT TO THE ENVIRONMENT

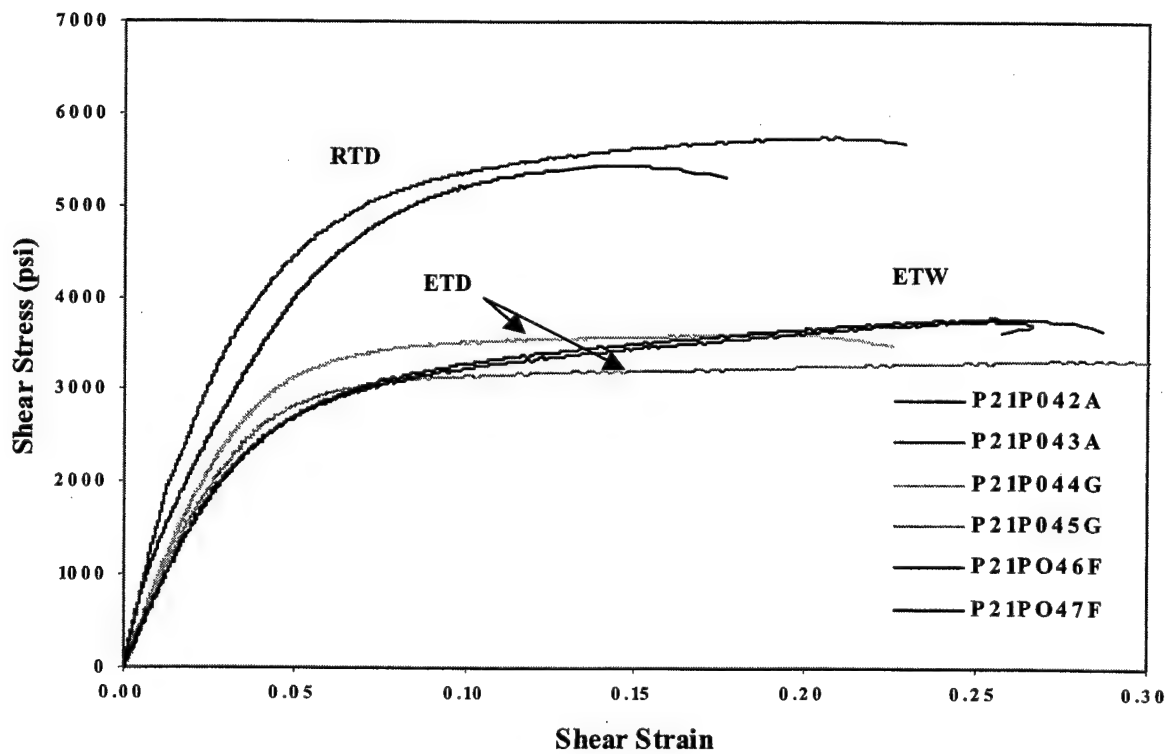


FIGURE A-20. CHARACTERISTIC SHEAR RESPONSE OF EA 9392 PASTE ADHESIVE (BOND LINE = 0.042") WITH RESPECT TO THE ENVIRONMENT

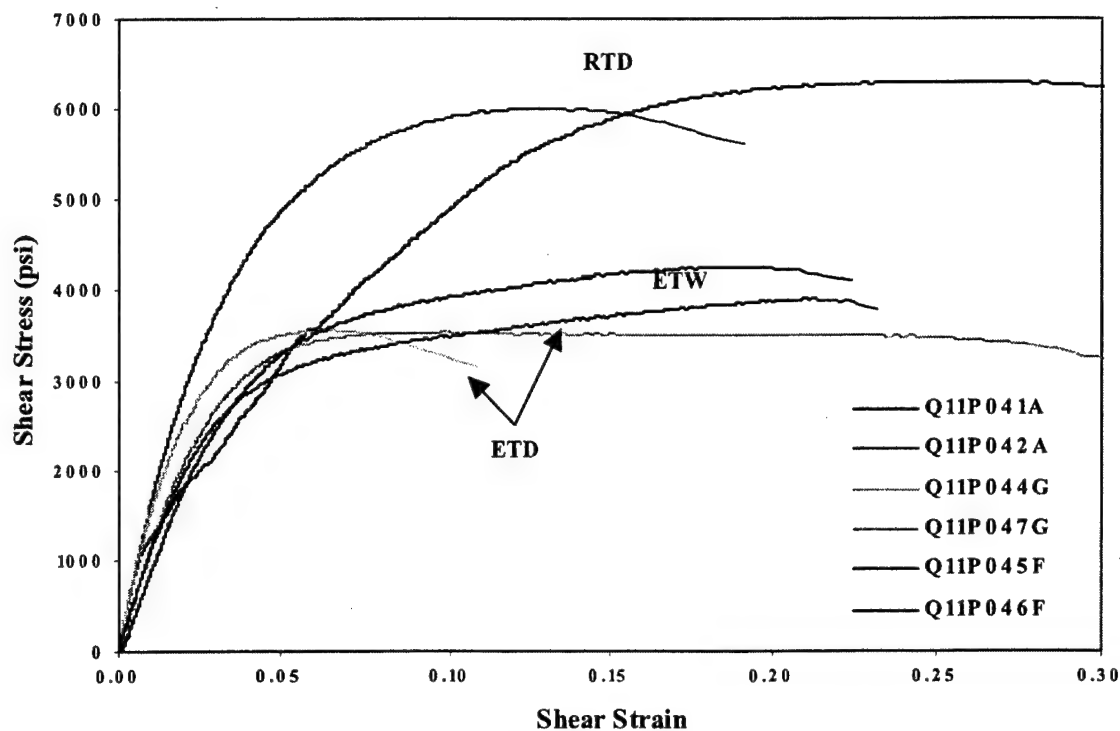


FIGURE A-21. CHARACTERISTIC SHEAR RESPONSE OF EA 9394 PASTE ADHESIVE (BOND LINE = 0.042") WITH RESPECT TO THE ENVIRONMENT

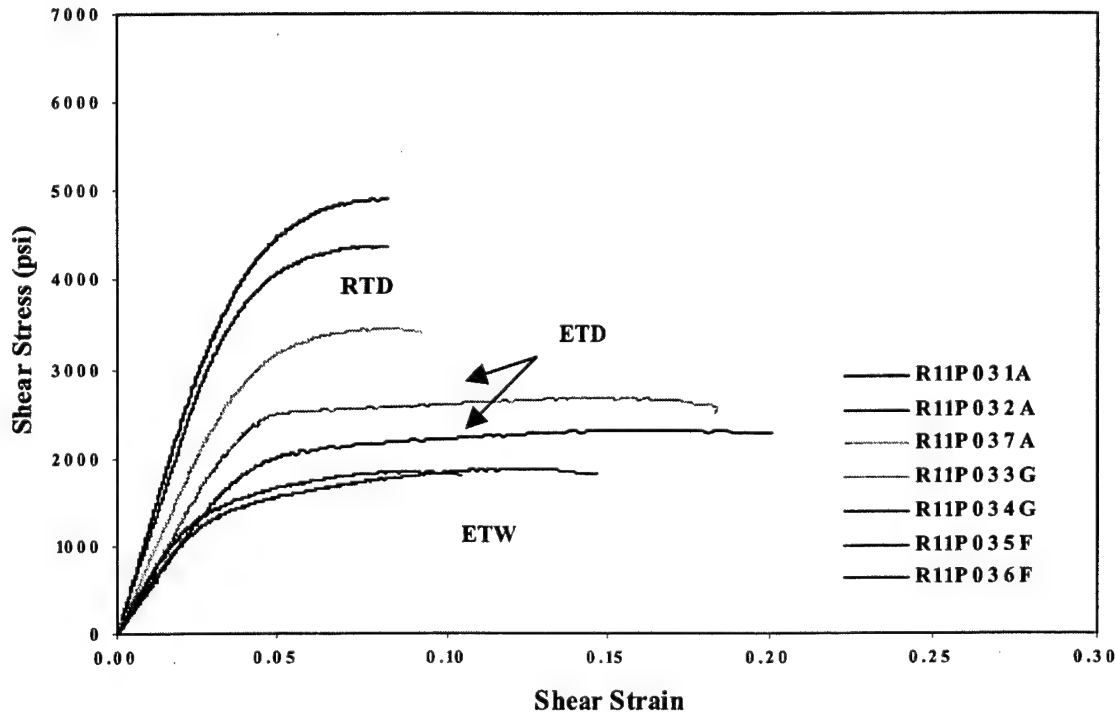


FIGURE A-22. CHARACTERISTIC SHEAR RESPONSE OF EA 9396 PASTE ADHESIVE (BOND LINE = 0.034") WITH RESPECT TO THE ENVIRONMENT

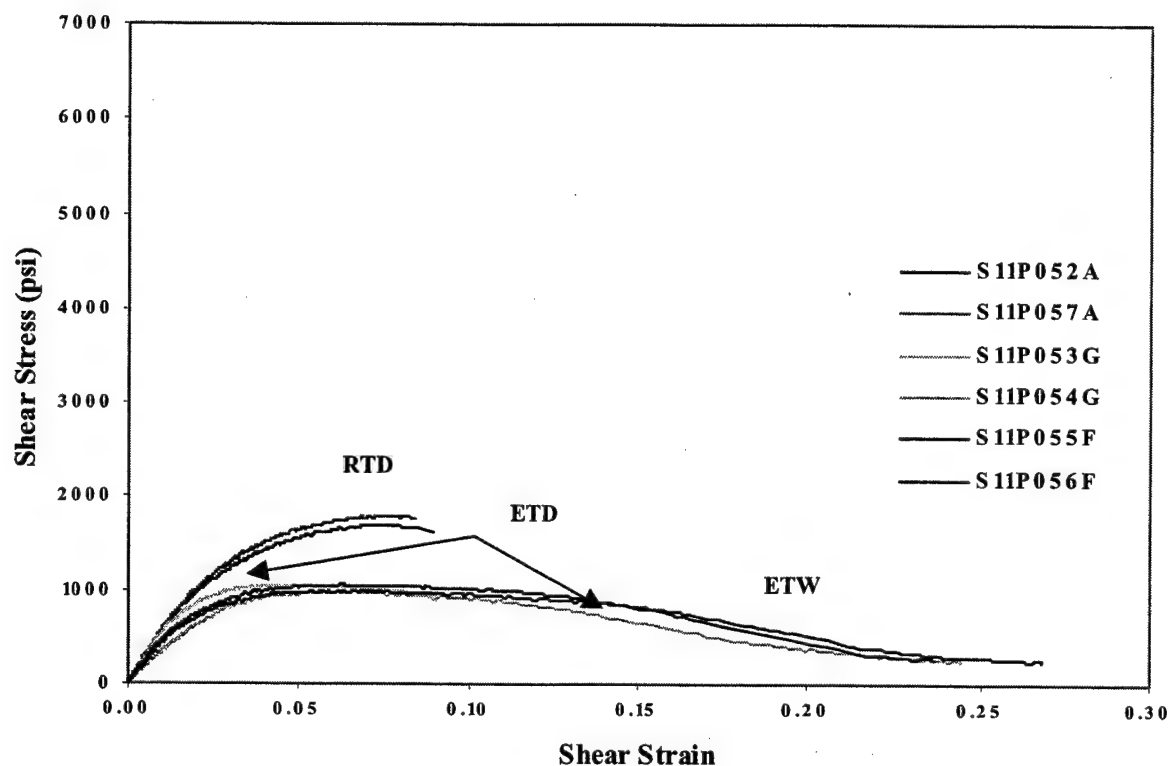


FIGURE A-23. CHARACTERISTIC SHEAR RESPONSE OF MGS L418 PASTE ADHESIVE (BOND LINE = 0.056") WITH RESPECT TO THE ENVIRONMENT

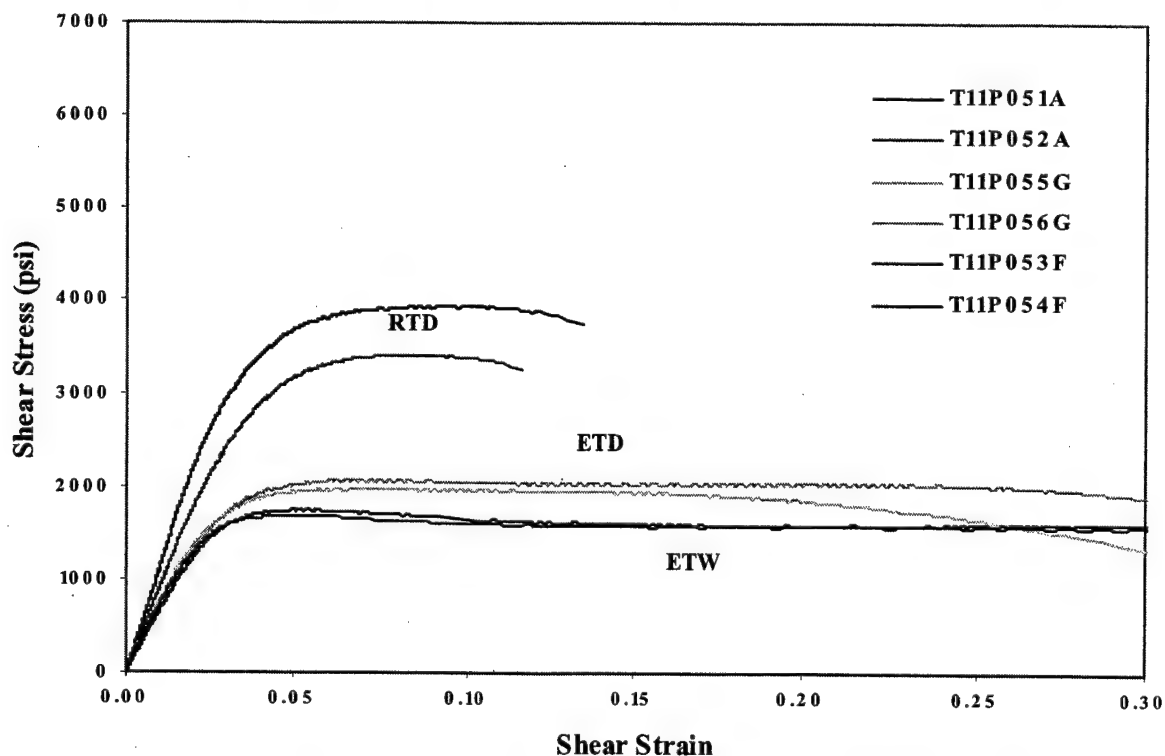


FIGURE A-24. CHARACTERISTIC SHEAR RESPONSE OF PTM&W ES 6292 PASTE ADHESIVE (BOND LINE = 0.052") WITH RESPECT TO THE ENVIRONMENT

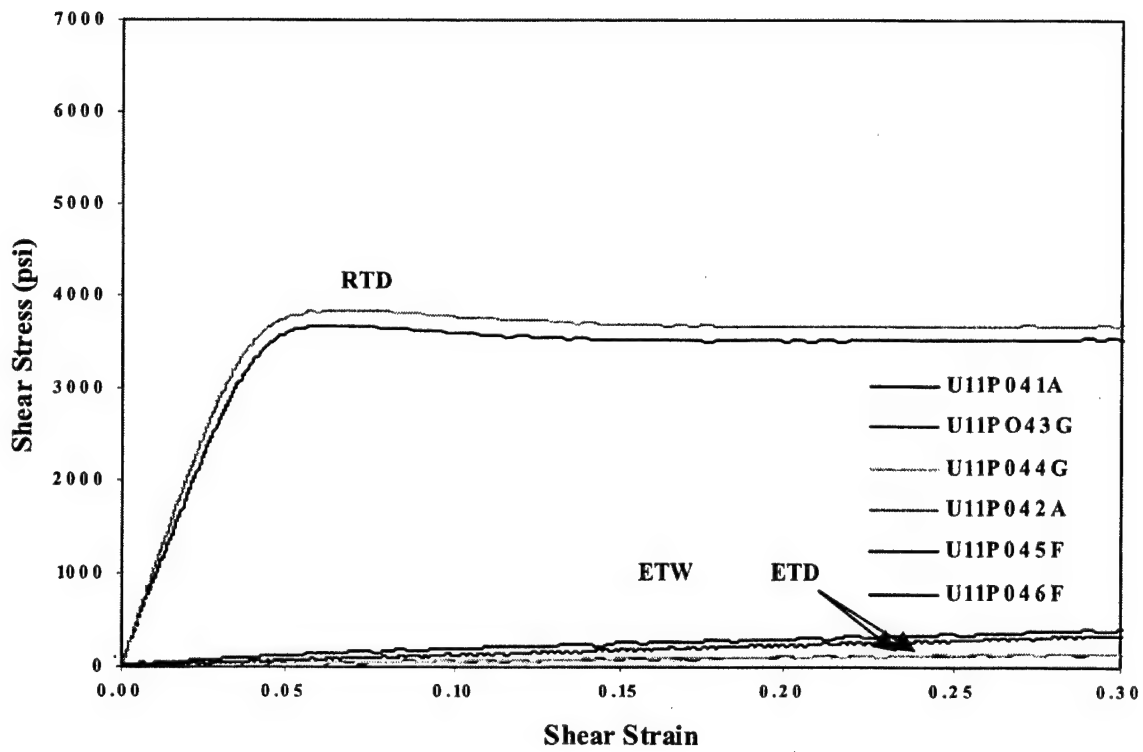


FIGURE A-25. CHARACTERISTIC SHEAR RESPONSE OF 3M DP-460EG PASTE ADHESIVE (BOND LINE = 0.045") WITH RESPECT TO THE ENVIRONMENT

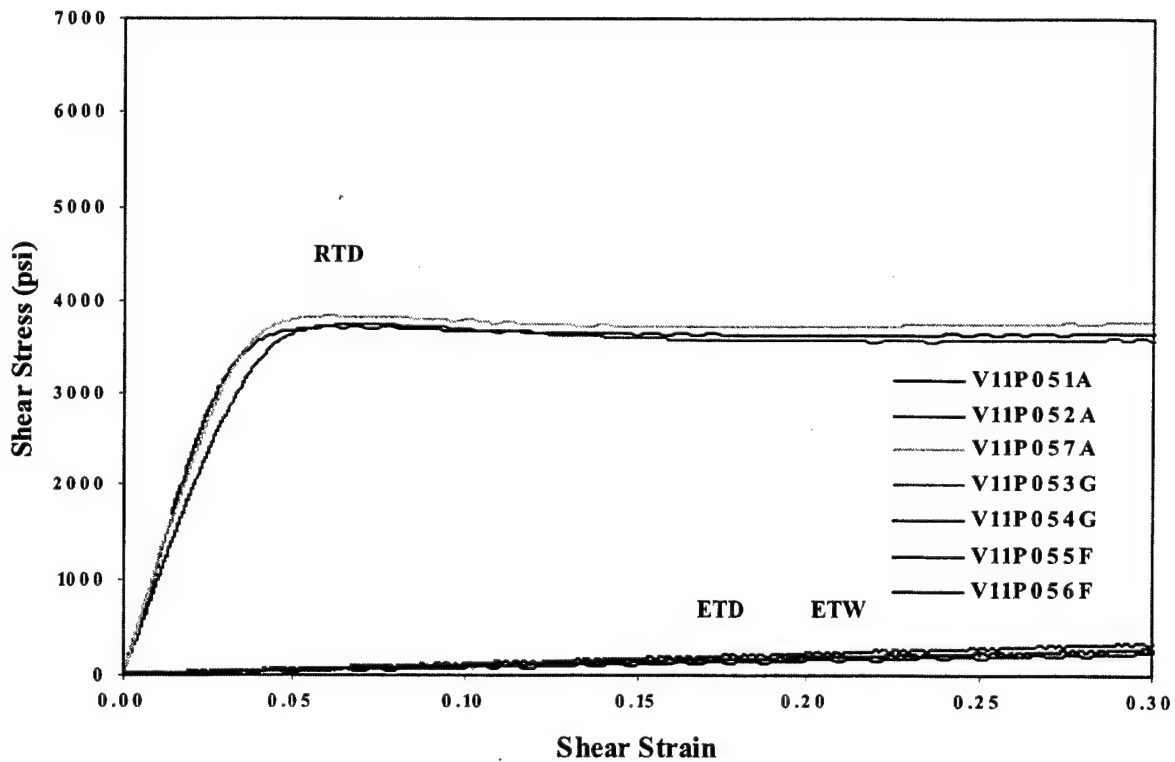


FIGURE A-26. CHARACTERISTIC SHEAR RESPONSE OF 3M DP-460NS PASTE ADHESIVE (BOND LINE = 0.040") WITH RESPECT TO THE ENVIRONMENT

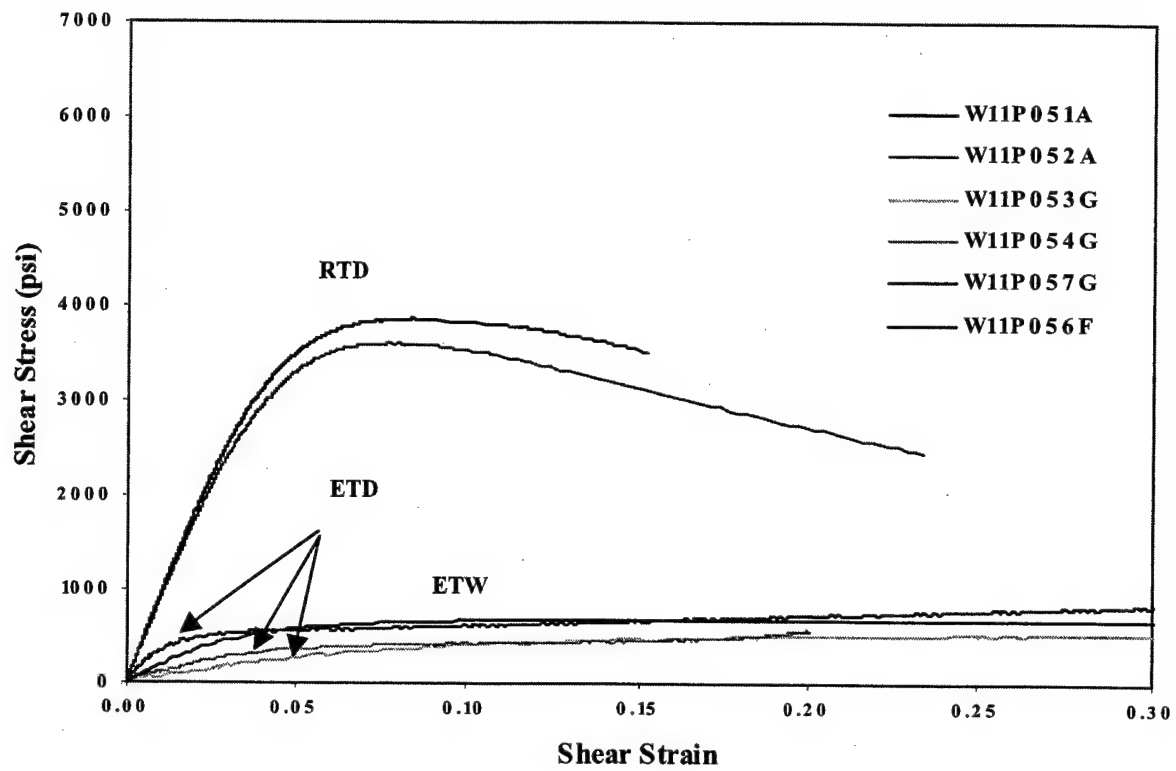


FIGURE A-27. CHARACTERISTIC SHEAR RESPONSE OF 3M DP-820 PASTE ADHESIVE (BOND LINE = 0.051") WITH RESPECT TO THE ENVIRONMENT

APPENDIX B—ADHESIVE APPARENT SHEAR STRENGTH AND MODULUS WITH
RESPECT TO THE ENVIRONMENT

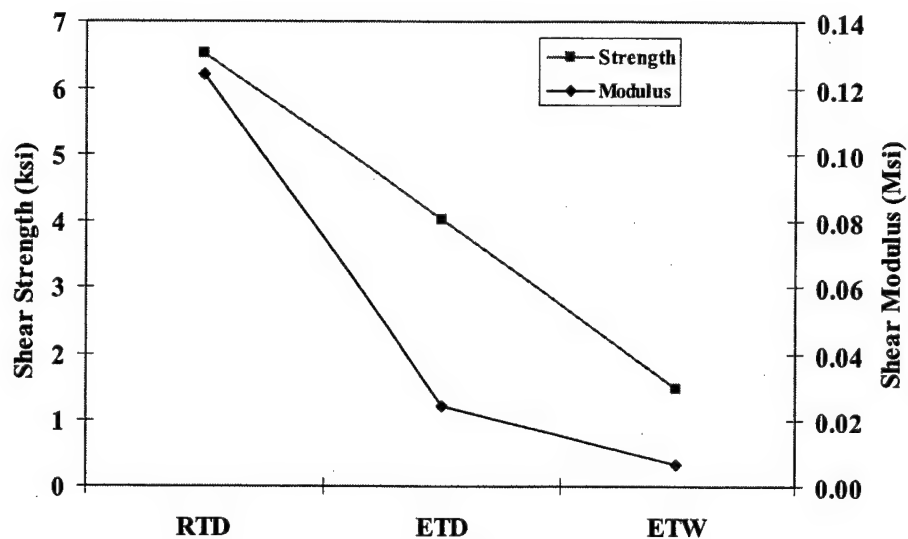


FIGURE B-1. APPARENT ADHESIVE SHEAR STRENGTH AND SHEAR MODULUS OF
AF 126 FILM ADHESIVE (BOND LINE = 0.013") WITH RESPECT TO THE
ENVIRONMENT

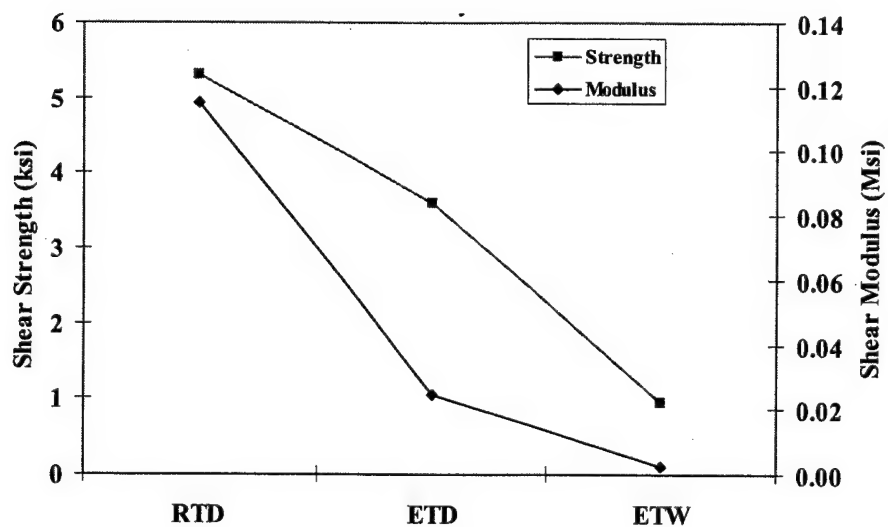


FIGURE B-2. APPARENT ADHESIVE SHEAR STRENGTH AND SHEAR MODULUS OF
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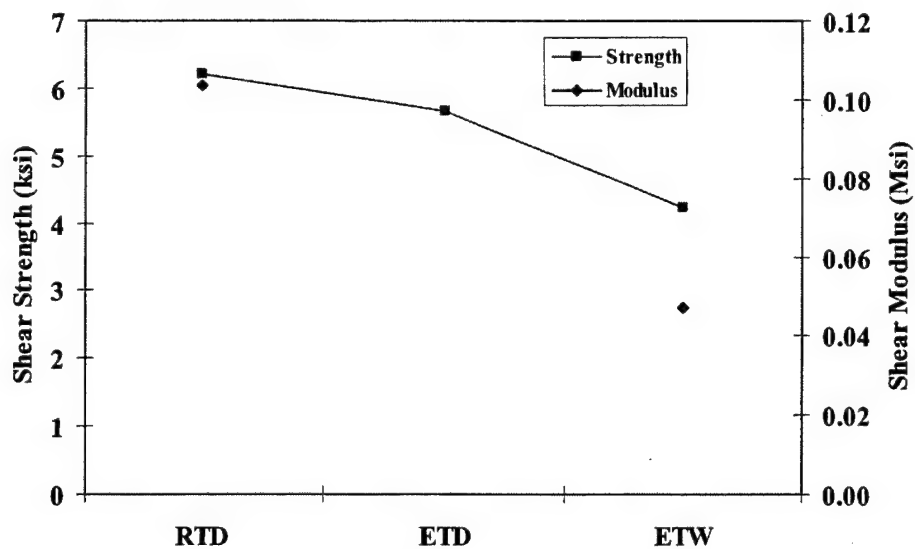


FIGURE B-3. APPARENT ADHESIVE SHEAR STRENGTH AND SHEAR MODULUS OF EA 9628 FILM ADHESIVE (BOND LINE = 0.010") WITH RESPECT TO THE ENVIRONMENT

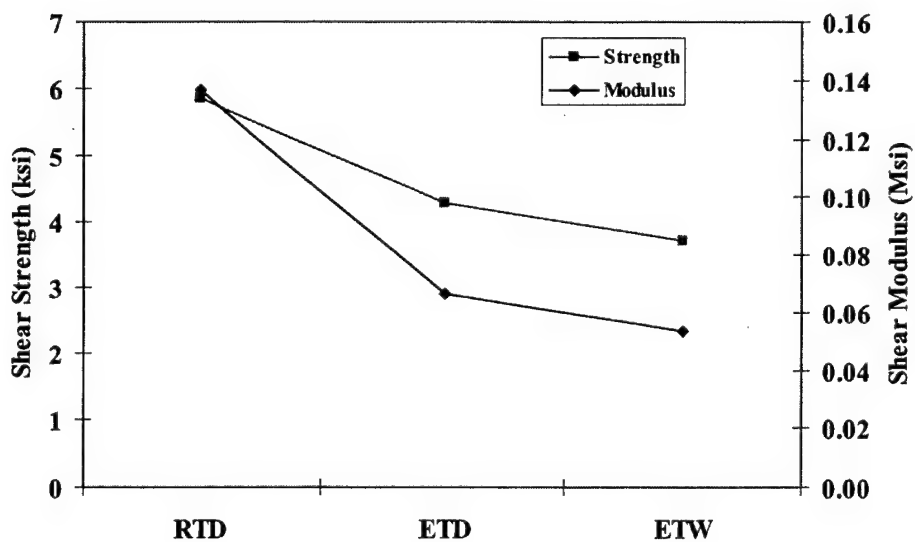


FIGURE B-4. APPARENT ADHESIVE SHEAR STRENGTH AND SHEAR MODULUS OF EA 9628 FILM ADHESIVE (BOND LINE = 0.031") WITH RESPECT TO THE ENVIRONMENT

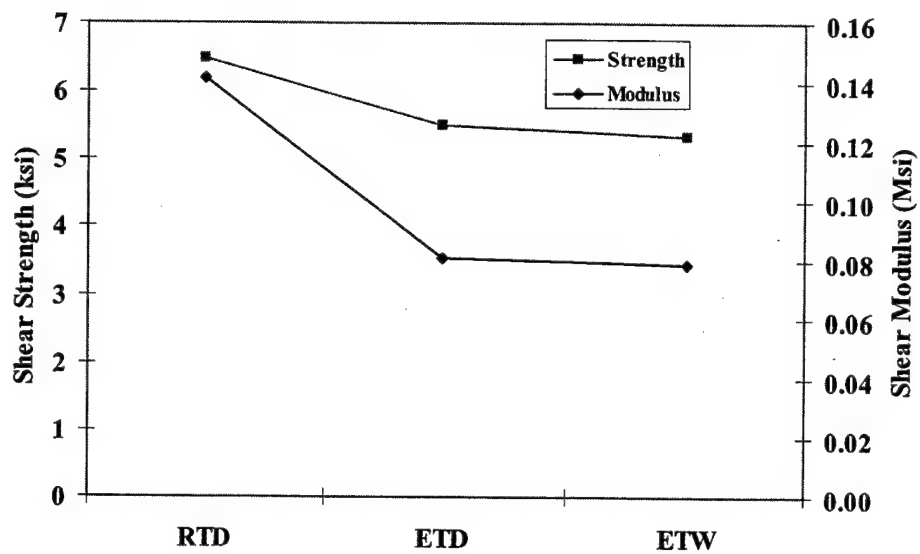


FIGURE B-5. APPARENT ADHESIVE SHEAR STRENGTH AND SHEAR MODULUS OF EA 9695 FILM ADHESIVE (BOND LINE = 0.011") WITH RESPECT TO THE ENVIRONMENT

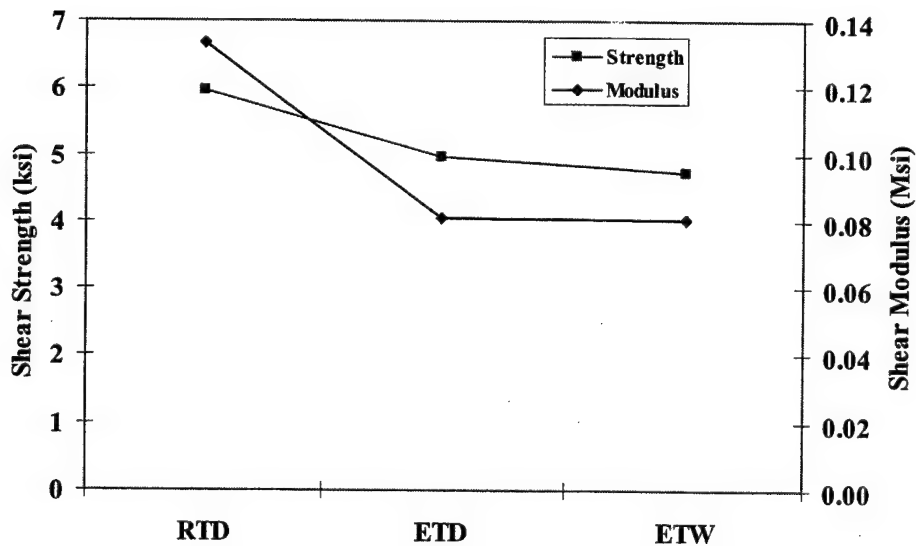


FIGURE B-6. APPARENT ADHESIVE SHEAR STRENGTH AND SHEAR MODULUS OF EA 9695 FILM ADHESIVE (BOND LINE = 0.034") WITH RESPECT TO THE ENVIRONMENT

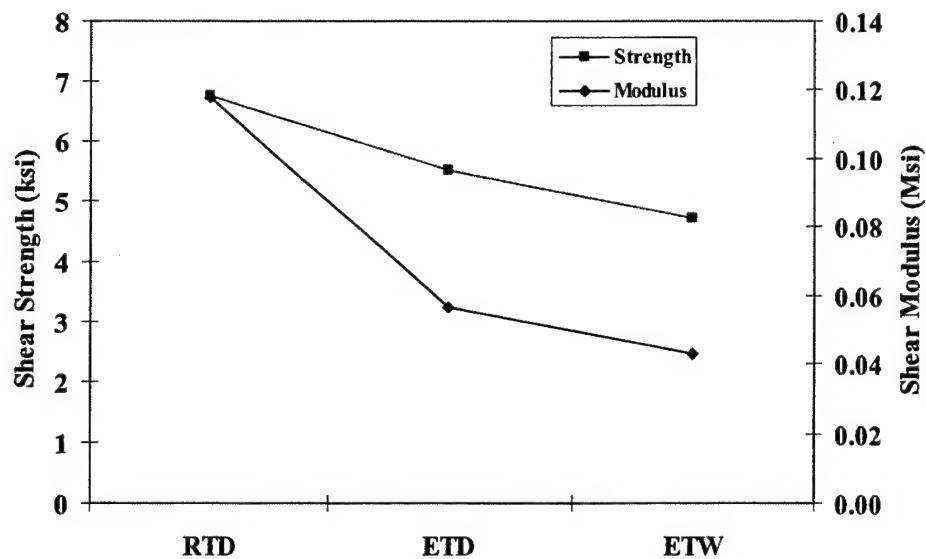


FIGURE B-7. APPARENT ADHESIVE SHEAR STRENGTH AND SHEAR MODULUS OF EA 9696 FILM ADHESIVE (BOND LINE = 0.011") WITH RESPECT TO THE ENVIRONMENT

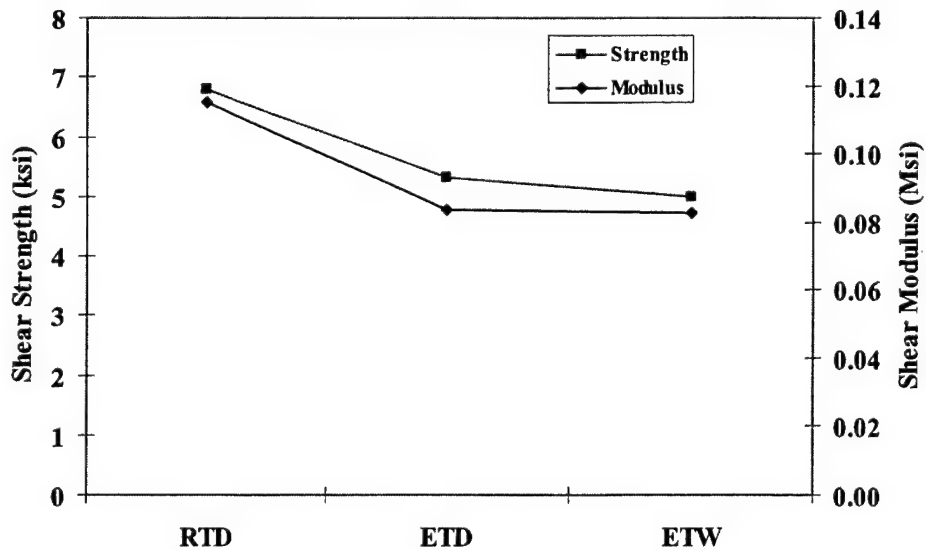


FIGURE B-8. APPARENT ADHESIVE SHEAR STRENGTH AND SHEAR MODULUS OF FM 300 FILM ADHESIVE (BOND LINE = 0.014") WITH RESPECT TO THE ENVIRONMENT

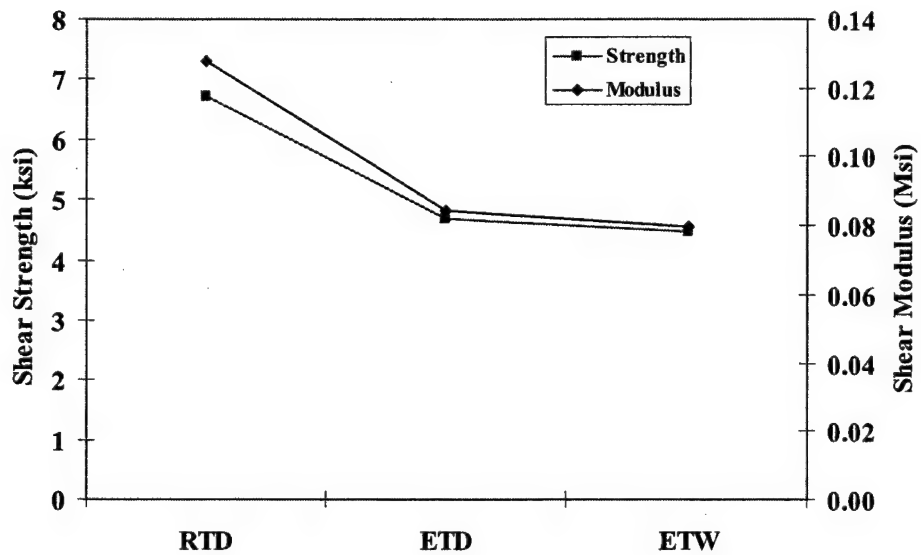


FIGURE B-9. APPARENT ADHESIVE SHEAR STRENGTH AND SHEAR MODULUS OF FM 300 FILM ADHESIVE (BOND LINE = 0.033") WITH RESPECT TO THE ENVIRONMENT

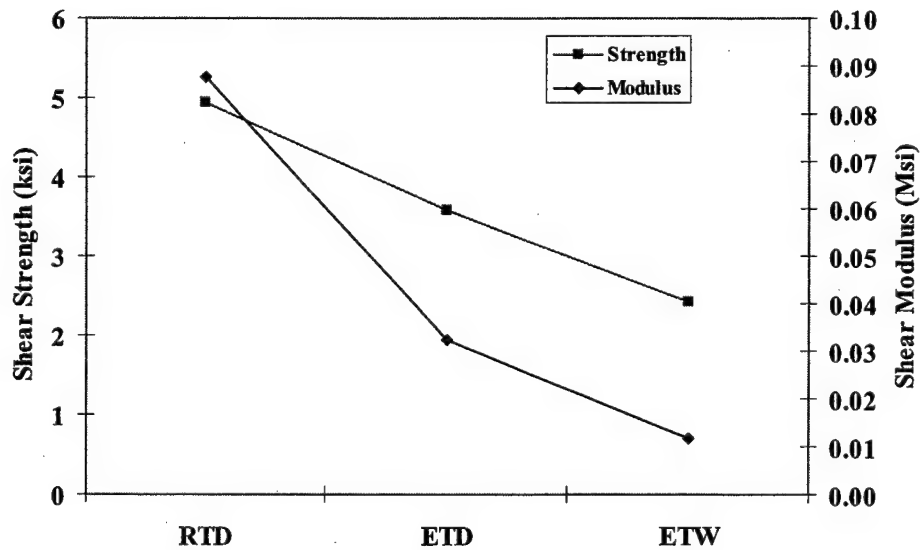


FIGURE B-10. APPARENT ADHESIVE SHEAR STRENGTH AND SHEAR MODULUS OF FM 300 FILM ADHESIVE (BOND LINE = 0.019") WITH RESPECT TO THE ENVIRONMENT

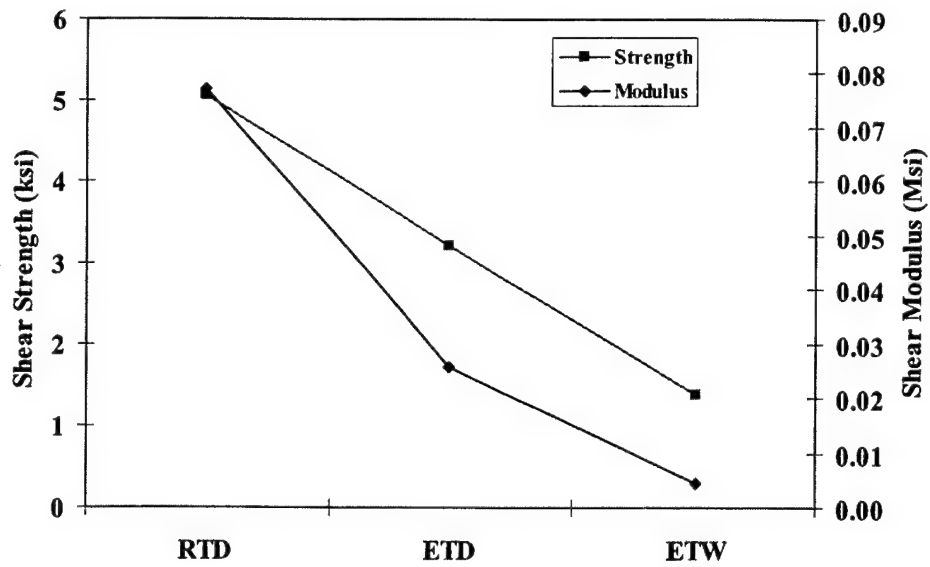


FIGURE B-11. APPARENT ADHESIVE SHEAR STRENGTH AND SHEAR MODULUS OF FM 300 FILM ADHESIVE (BOND LINE = 0.028") WITH RESPECT TO THE ENVIRONMENT

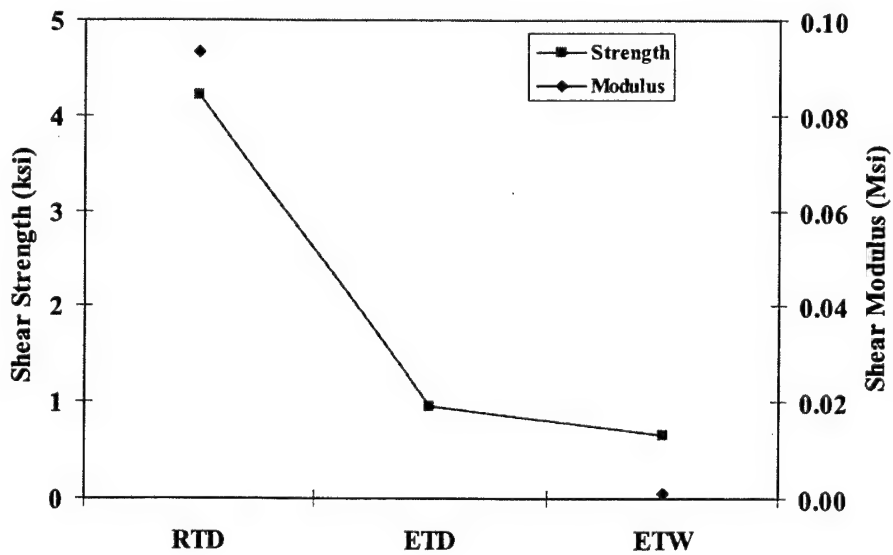


FIGURE B-12. APPARENT ADHESIVE SHEAR STRENGTH AND SHEAR MODULUS OF EA 9309.3NA PASTE ADHESIVE (BOND LINE = 0.040") WITH RESPECT TO THE ENVIRONMENT

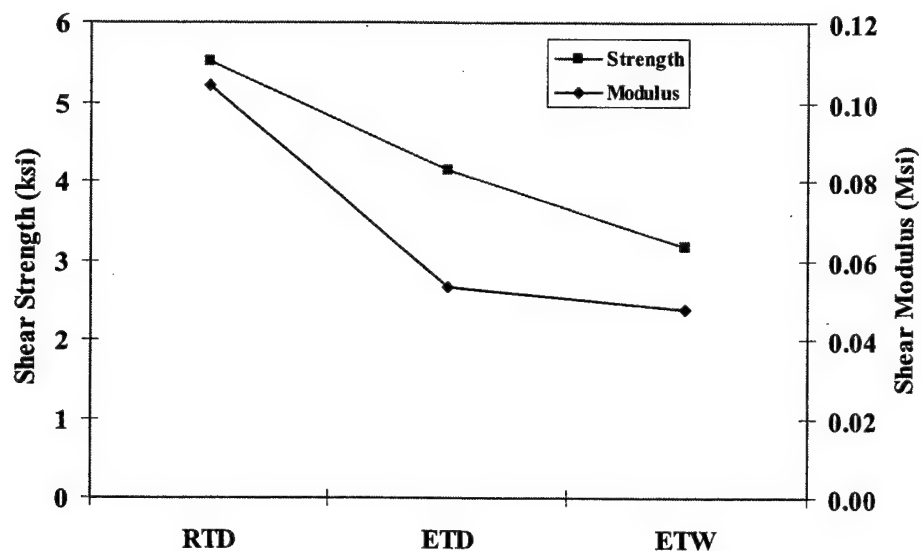


FIGURE B-13. APPARENT ADHESIVE SHEAR STRENGTH AND SHEAR MODULUS OF EA 9346.5 PASTE ADHESIVE (BOND LINE = 0.044") WITH RESPECT TO THE ENVIRONMENT

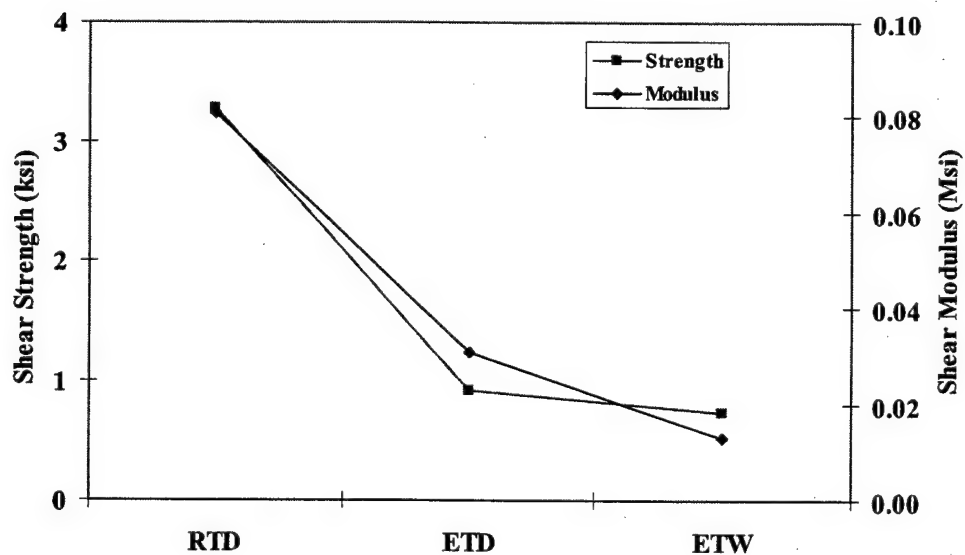


FIGURE B-14. APPARENT ADHESIVE SHEAR STRENGTH AND SHEAR MODULUS OF EA 9359.3 PASTE ADHESIVE (BOND LINE = 0.032") WITH RESPECT TO THE ENVIRONMENT

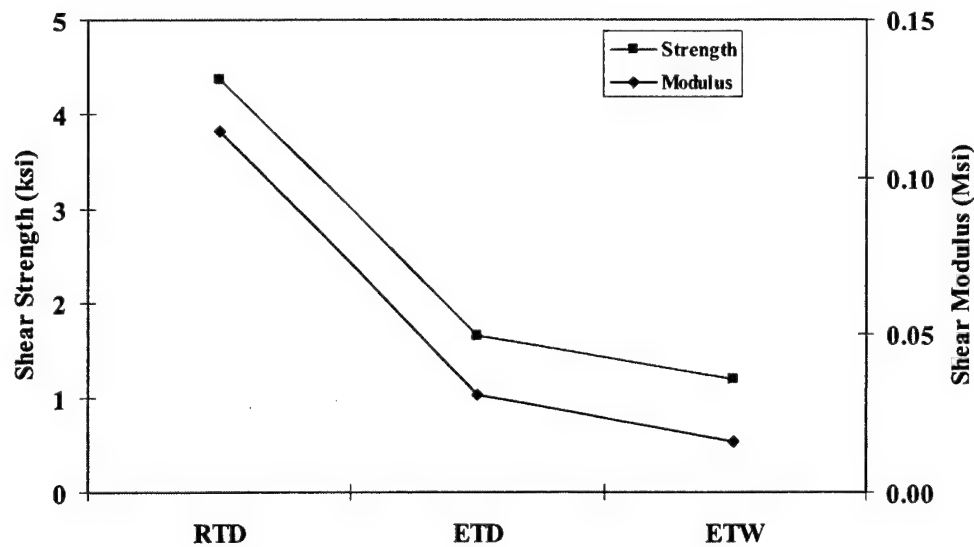


FIGURE B-15. APPARENT ADHESIVE SHEAR STRENGTH AND SHEAR MODULUS OF EA 9359.3 PASTE ADHESIVE (BOND LINE = 0.038") WITH RESPECT TO THE ENVIRONMENT

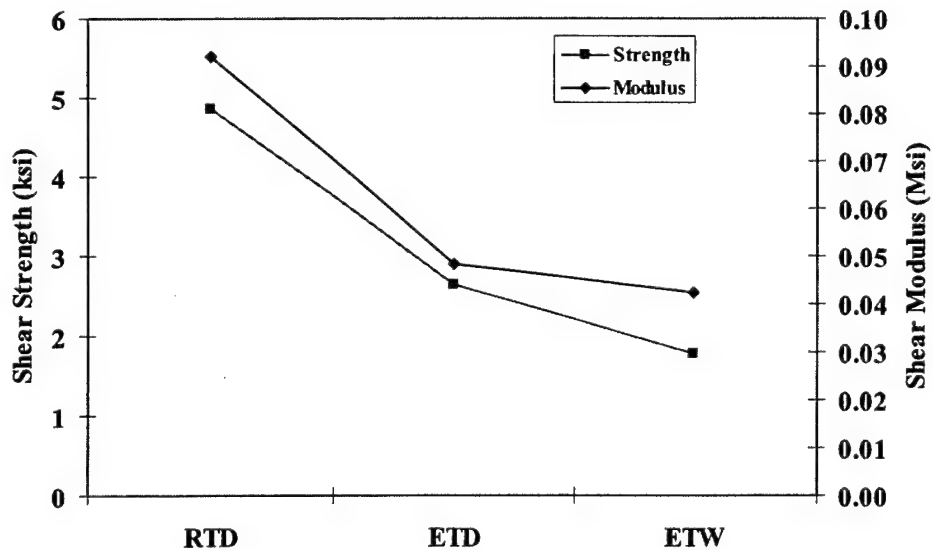


FIGURE B-16. APPARENT ADHESIVE SHEAR STRENGTH AND SHEAR MODULUS OF EA 9360 PASTE ADHESIVE (BOND LINE = 0.036") WITH RESPECT TO THE ENVIRONMENT

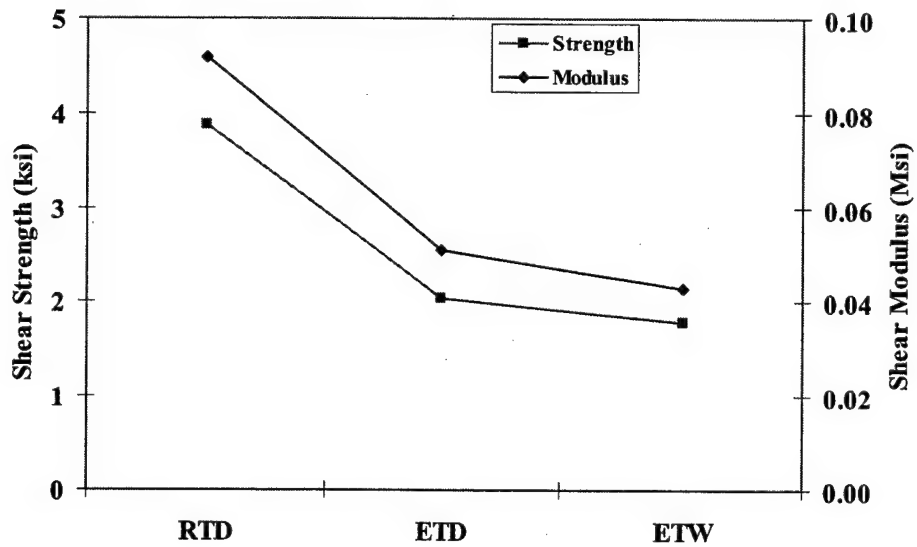


FIGURE B-17. APPARENT ADHESIVE SHEAR STRENGTH AND SHEAR MODULUS OF EA 9360 PASTE ADHESIVE (BOND LINE = 0.032") WITH RESPECT TO THE ENVIRONMENT

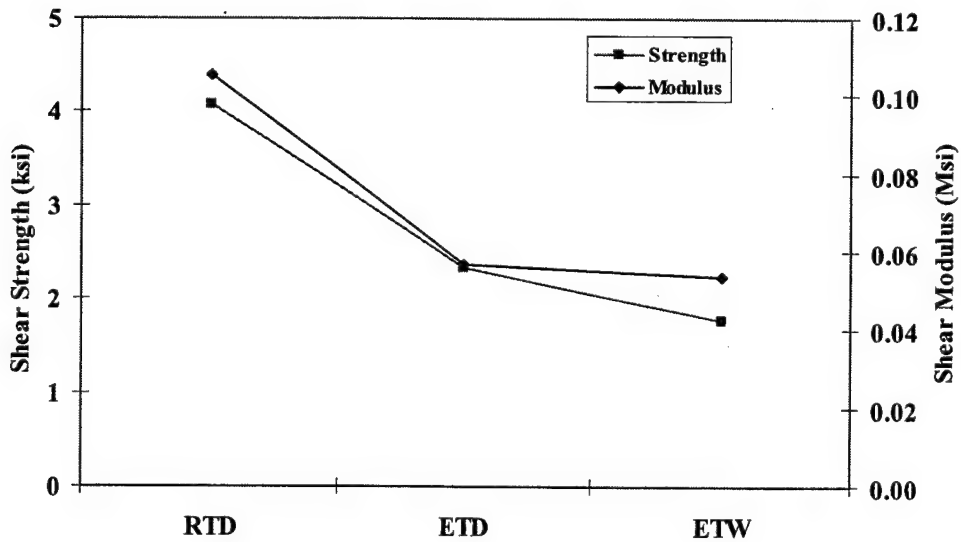


FIGURE B-18. APPARENT ADHESIVE SHEAR STRENGTH AND SHEAR MODULUS OF EA 9360 PASTE ADHESIVE (BOND LINE = 0.051") WITH RESPECT TO THE ENVIRONMENT

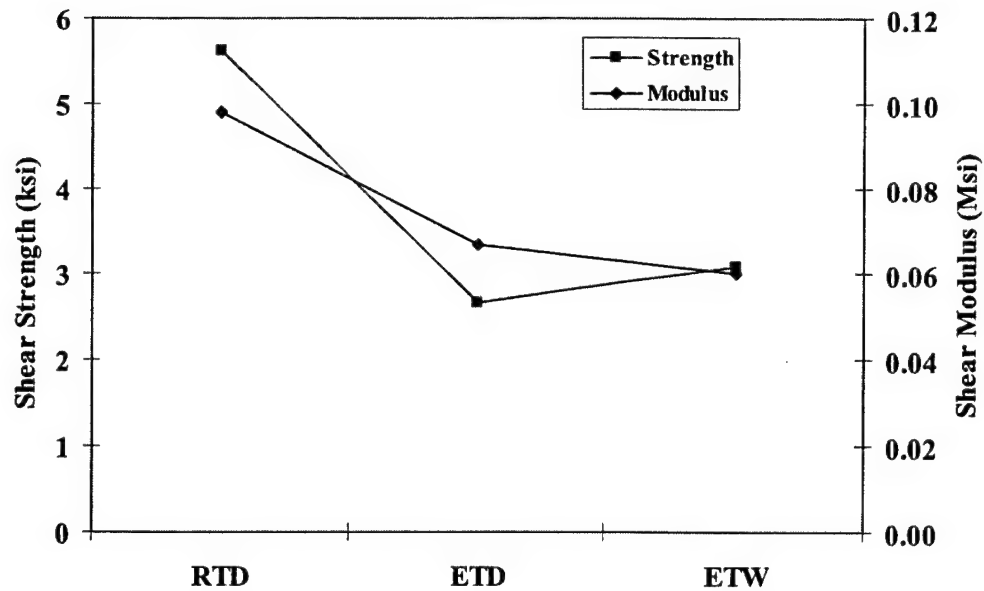


FIGURE B-19. APPARENT ADHESIVE SHEAR STRENGTH AND SHEAR MODULUS OF EA 9392 PASTE ADHESIVE (BOND LINE = 0.033") WITH RESPECT TO THE ENVIRONMENT

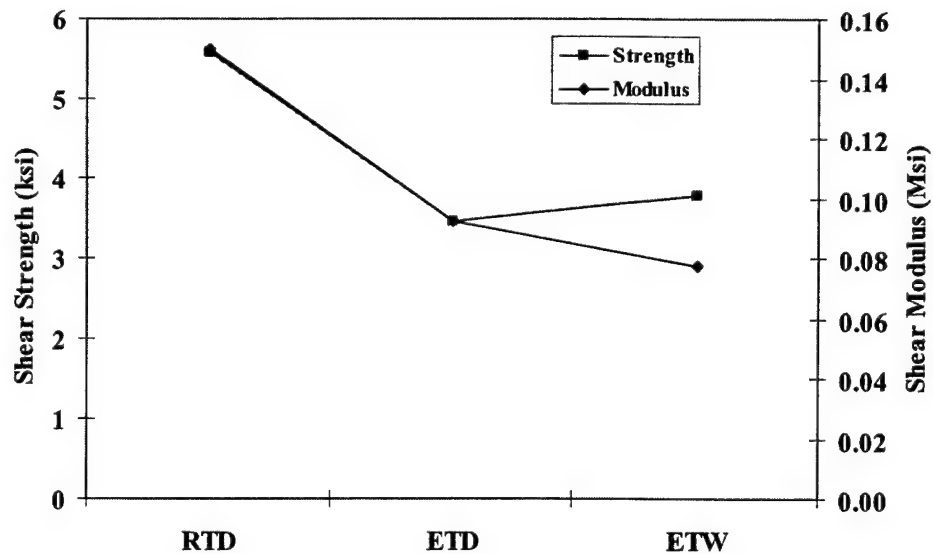


FIGURE B-20. APPARENT ADHESIVE SHEAR STRENGTH AND SHEAR MODULUS OF EA 9392 PASTE ADHESIVE (BOND LINE = 0.042") WITH RESPECT TO THE ENVIRONMENT

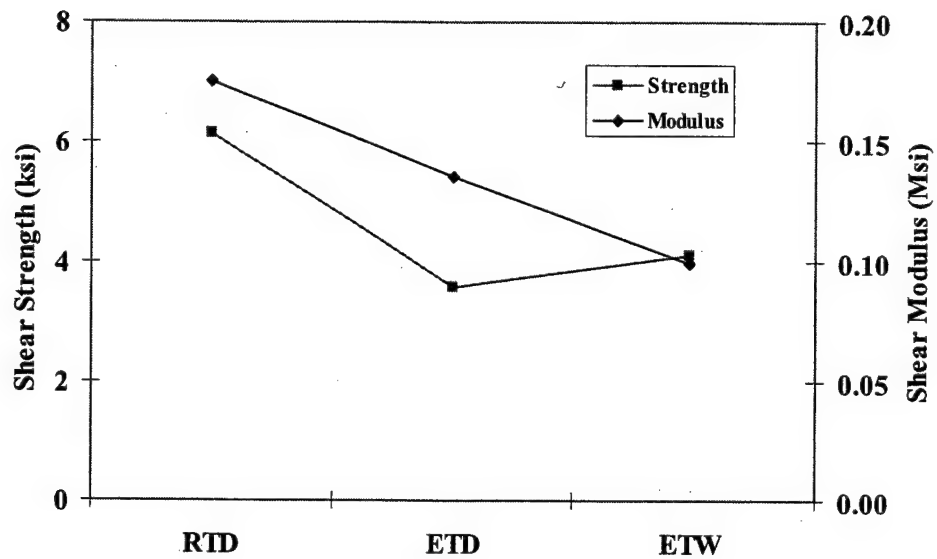


FIGURE B-21. APPARENT ADHESIVE SHEAR STRENGTH AND SHEAR MODULUS OF EA 9394 PASTE ADHESIVE (BOND LINE = 0.042") WITH RESPECT TO THE ENVIRONMENT

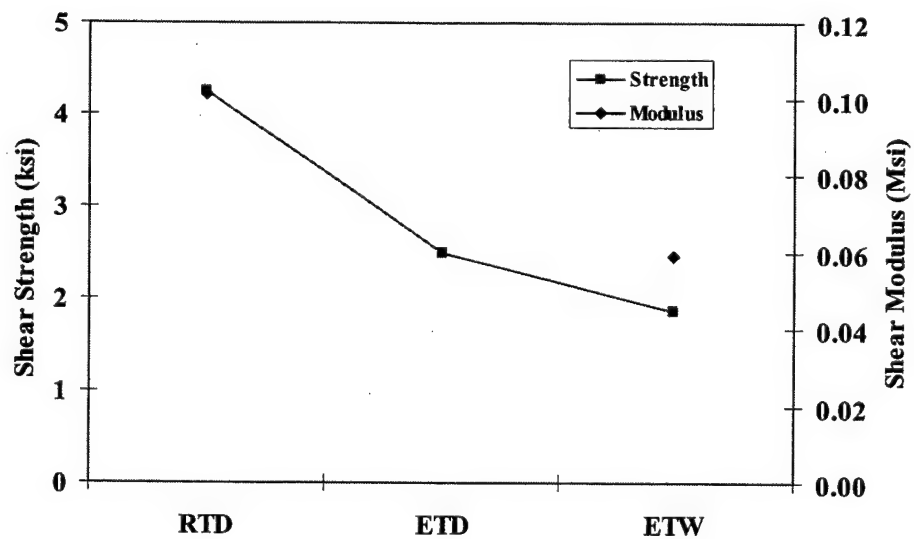


FIGURE B-22. APPARENT ADHESIVE SHEAR STRENGTH AND SHEAR MODULUS OF EA 9396 PASTE ADHESIVE (BOND LINE = 0.034") WITH RESPECT TO THE ENVIRONMENT

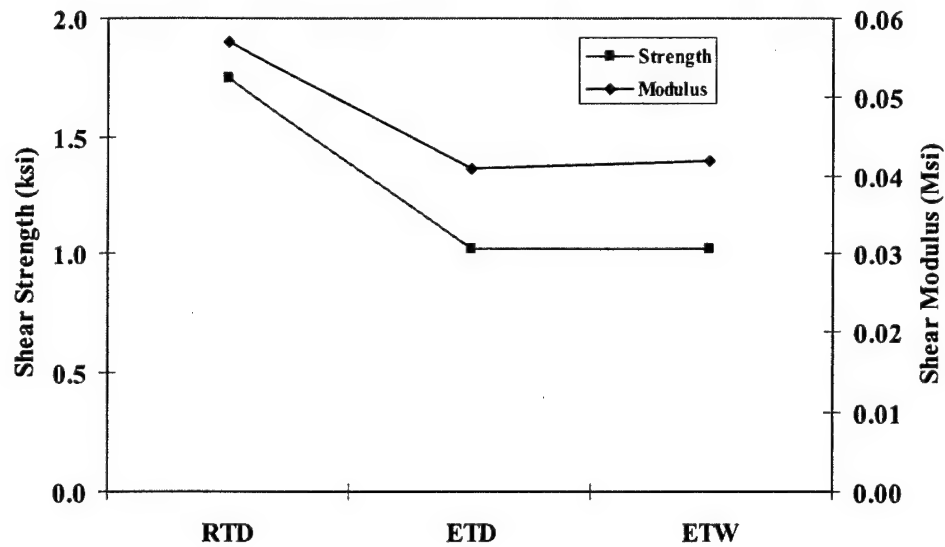


FIGURE B-23. APPARENT ADHESIVE SHEAR STRENGTH AND SHEAR MODULUS OF MGS L418 PASTE ADHESIVE (BOND LINE = 0.056") WITH RESPECT TO THE ENVIRONMENT

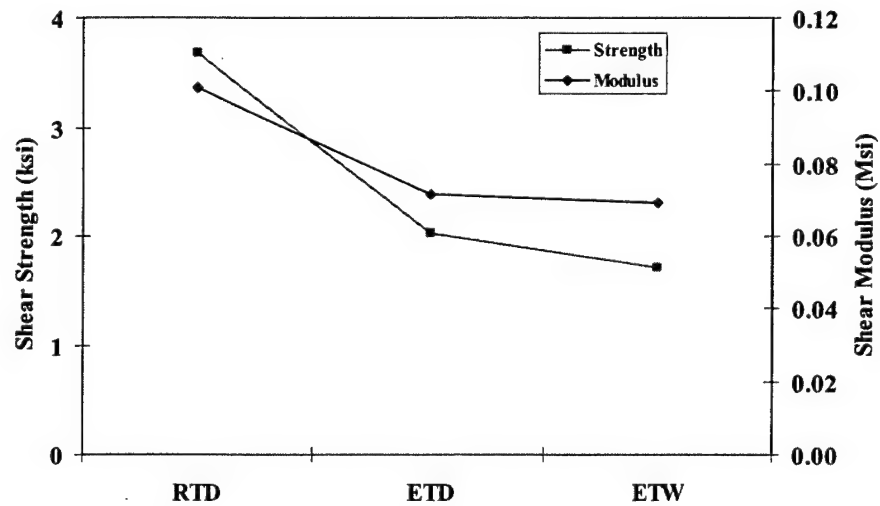


FIGURE B-24. APPARENT ADHESIVE SHEAR STRENGTH AND SHEAR MODULUS OF PTM&W ES 6292 PASTE ADHESIVE (BOND LINE = 0.052") WITH RESPECT TO THE ENVIRONMENT

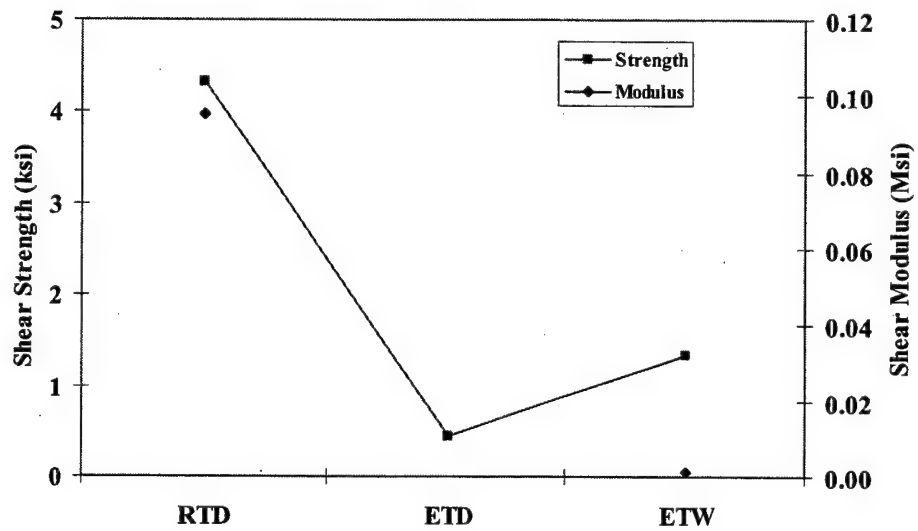


FIGURE B-25. APPARENT ADHESIVE SHEAR STRENGTH AND SHEAR MODULUS OF 3M DP-460 EG PASTE ADHESIVE (BOND LINE = 0.045") WITH RESPECT TO THE ENVIRONMENT

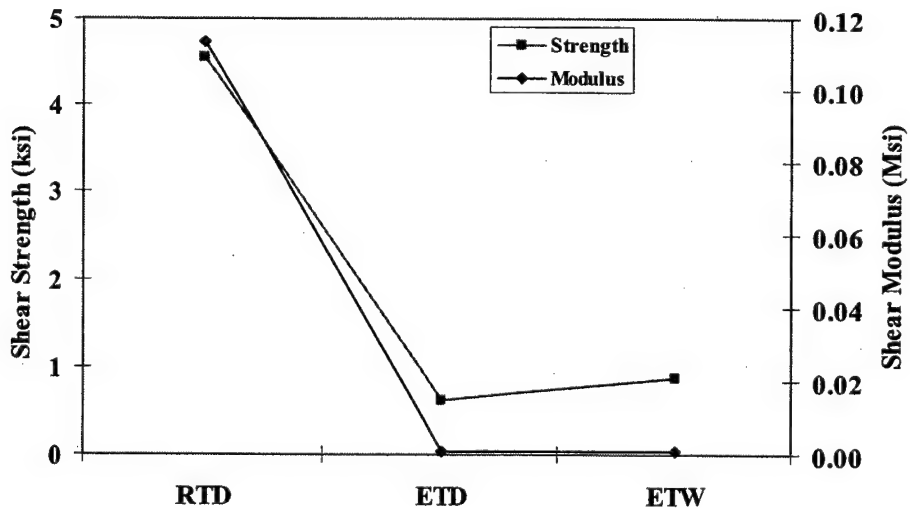


FIGURE B-26. APPARENT ADHESIVE SHEAR STRENGTH AND SHEAR MODULUS OF 3M DP-460 NS PASTE ADHESIVE (BOND LINE = 0.040") WITH RESPECT TO THE ENVIRONMENT

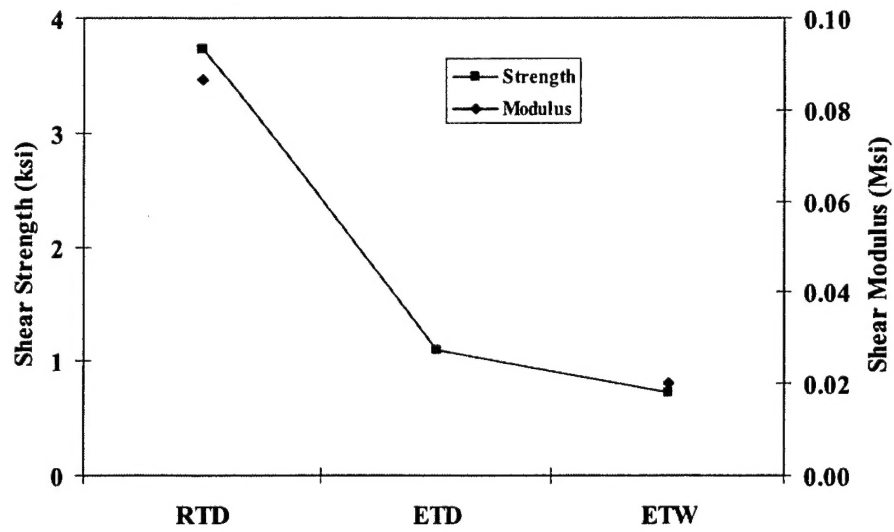


FIGURE B-27. APPARENT ADHESIVE SHEAR STRENGTH AND SHEAR MODULUS OF 3M DP-820 PASTE ADHESIVE (BOND LINE = 0.051") WITH RESPECT TO THE ENVIRONMENT

APPENDIX C—FAILURE MODES WITH RESPECT TO THE ENVIRONMENT

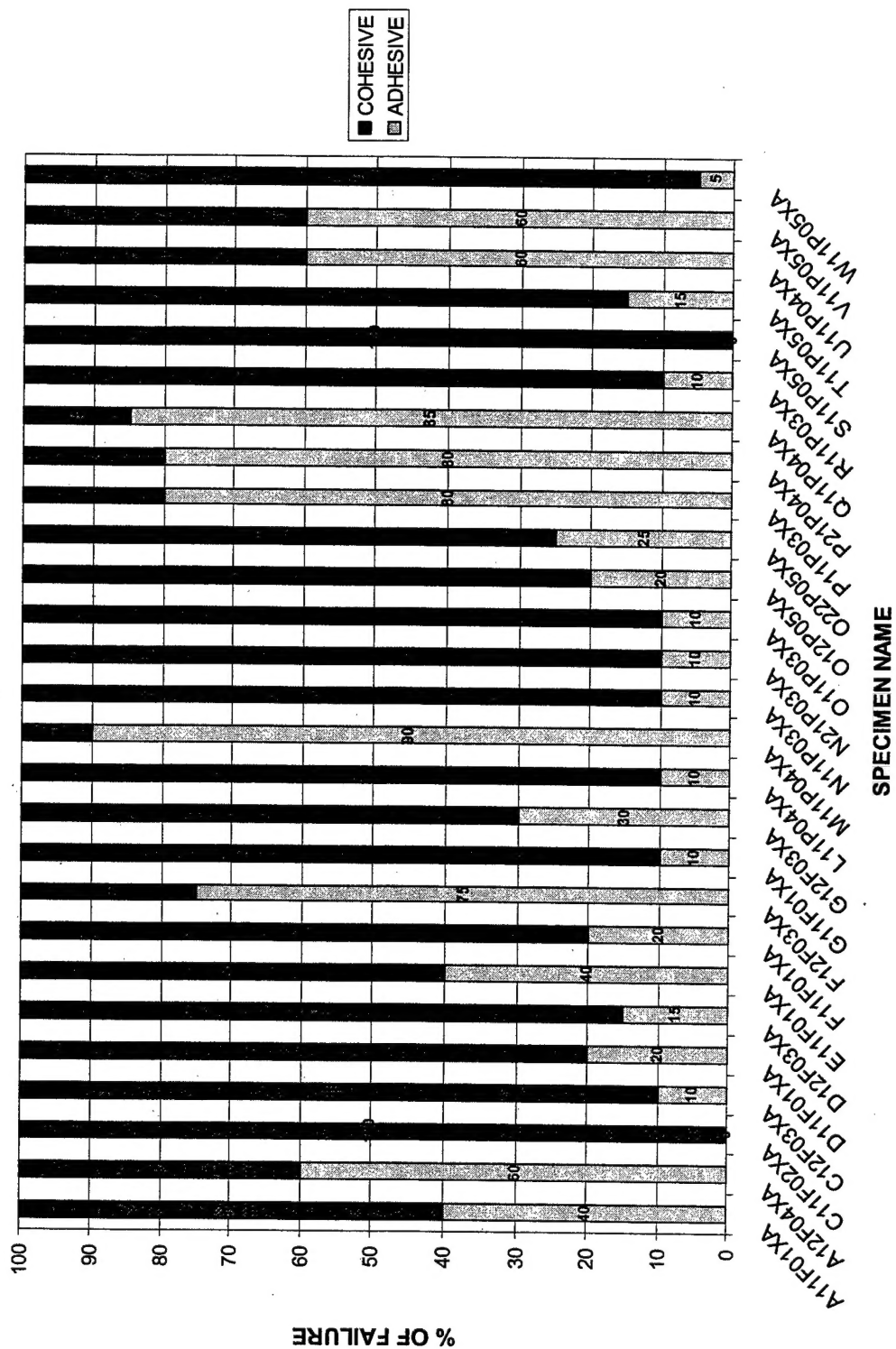


FIGURE C-1. FAILURE MODES FOR RTD SPECIMENS

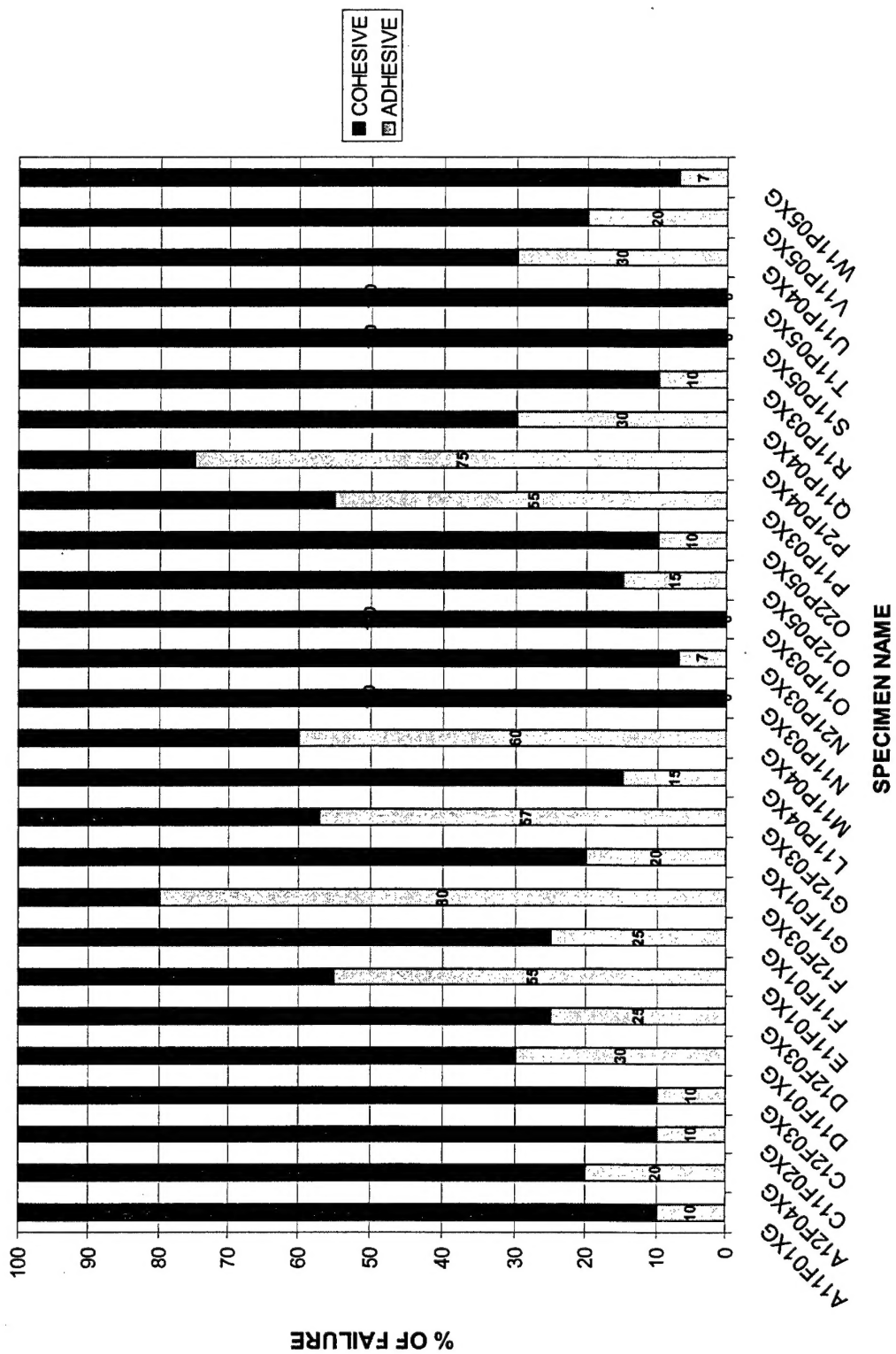


FIGURE C-2. FAILURE MODES FOR ETD SPECIMENS

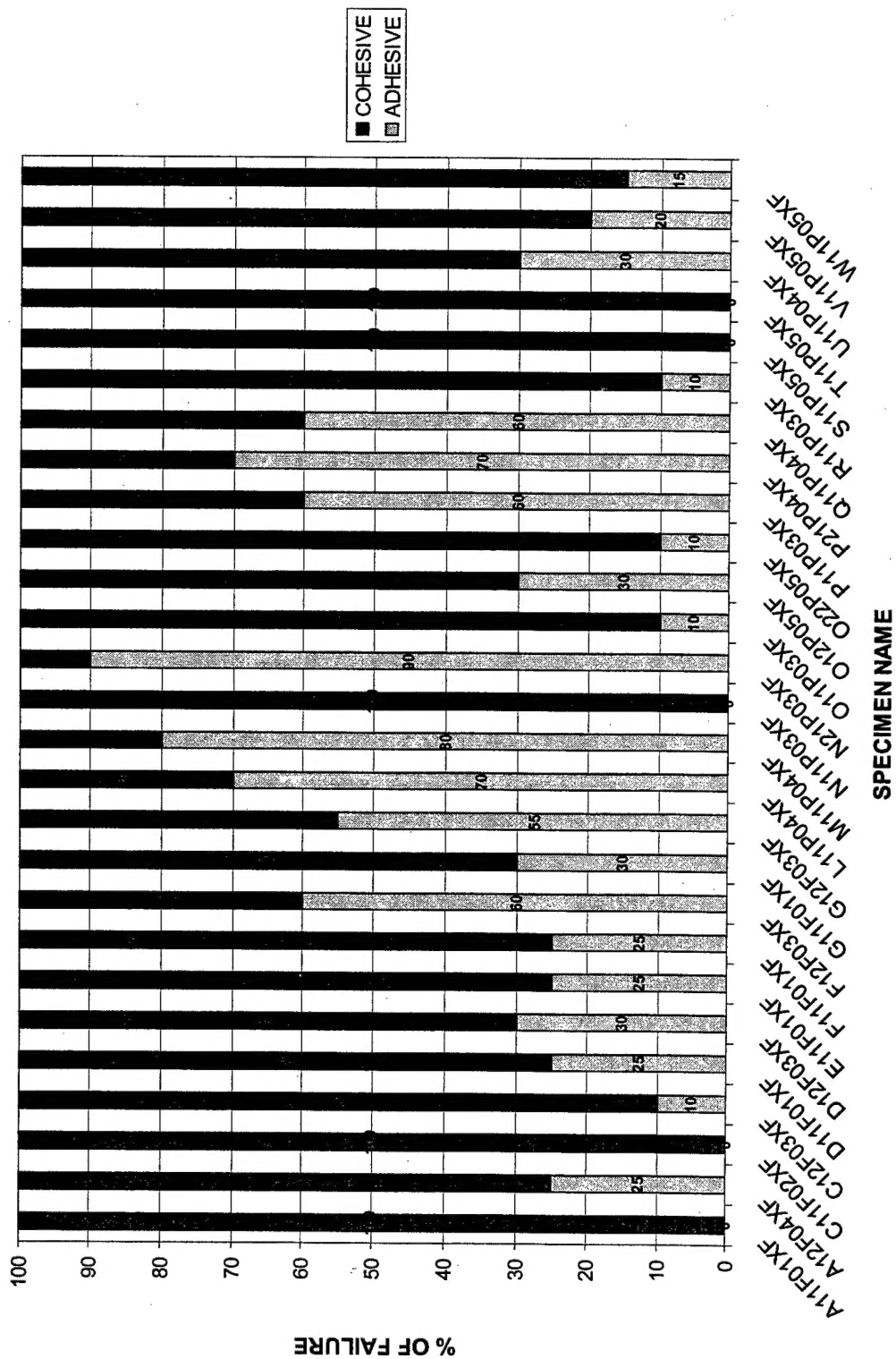


FIGURE C-3. FAILURE MODES FOR ETW SPECIMENS